UNIWERSYTET MEDYCZNY
IM. PIASTÓW ŚLĄSKICH WE WROCŁAWIU

Anna Ewa Kuc

Powikłania w leczeniu ortodontycznym wad w wymiarze strzałkowym

Promotor:

Prof. dr. hab. n. med. Michał Sarul

Promotor pomocniczy:

Dr. n. med. Jacek Kotuła

Katedra i Zakład Stomatologii Zintegrowanej

Recenzenci:

1. Dr.hab.n.med. Agnieszka Machorowska-Pieniążek
2. Dr.hab.n.med. Agnieszka Lasota
3. Dr.hab.n.med. Monika Machoy

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SPIS TREŚCI

1. Wykaz zastosowanych skrótów

PDL	Więzadła przyzębia
OIIRR	Ortodontycznie indukowana zapalna resorpcja korzeni zeba
CBCT	Stożkowa tomografia komputerowa
TISAD	Tymczasowe zakotwienie szkieletowe
R&R	Łączny błąd powtarzalności i odtwarzalności
ICC	Korelacja wewnątrzklasowa
BP	Błąd powtarzalności
BO	Błąd odtwarzalności
ZI	Zmienność indywidulana pacjenta
FEA	Analiza metodą elementów skończonych
FEM	Model elementów skończonych

2.Wykaz publikacji stanowiących rozprawę doktorską

Lp	Tytuł	Impact Factor	Punty MNiSW
1	Kotuła J, Kuc AE, Lis J, Kawala B, Sarul M. New Sagittal and Vertical Cephalometric Analysis Methods: A Systematic Review. Diagnostics. 2022; 12(7):1723.	3,6	70
2	Kotuła J, Kuc A, Szeląg E, Babczyńska A, Lis J, Matys J, Kawala B, Sarul M. Comparison of Diagnostic Validity of Cephalometric Analyses of the ANB Angle and Tau Angle for Assessment of the Sagittal Relationship of Jaw and Mandible. Journal of Clinical Medicine. 2023; 12(19):6333.	3,9	140
3	Kuc AE, Kotuła J, Nahajowski M, Warnecki M, Lis J, Amm E, Kawala B, Sarul M. Methods of Anterior Torque Control during Retraction: A Systematic Review. Diagnostics. 2022; 12(7):1611	3,6	70
4	Kuc AE, Kotuła J, Nawrocki J, Kulgawczyk M, Kawala B, Lis J, Sarul M. Bone Remodeling of Maxilla after Retraction of Incisors during Orthodontic Treatment with Extraction of Premolars Based on CBCT Study: A Systematic Review. Journal of Clinical Medicine. 2024; 13(5):1503. https://doi.org/10.3390/jcm13051503	3,9	140
5	Kuc AE, Sybilski K, Kotuła J, Piątkowski G, Kawala B, Lis J, Saternus S, Sarul M. The Hydrostatic Pressure Distribution in the Periodontal Ligament and the Risk of Root Resorption—A Finite Element Method (FEM) Study on the Nonlinear Innovative Model. Materials. 2024; 17(7):1661.	3,4	140
6	Kuc AE, Kotuła J, Nawrocki J, Babczyńska A, Lis J, Kawala B, Sarul M. The Assessment of the Rank of Torque Control during Incisor Retraction and Its	3,9	140

	Impact on the Resorption of Maxillary Central Incisor Roots According to Incisive Canal Anatomy—Systematic Review. Journal of Clinical Medicine. 2023; 12(8):2774.		
7	**Kuc AE, Kotuła J, Nawrocki J, Szeląg E, Kawala B, Lis J, Sarul M. Morphological Evaluation of the Incisive Canal in the Aspect of the Diagnosis and Planning of Orthodontic Treatment—CBCT Study. Applied Sciences. 2023; 13(21):12010**	**2,7**	**100**
	Razem	**25**	**800**

3. STRESZCZENIE

Wstęp

Wady klasy II dominują zarówno w populacjach kaukaskich Europy północnej, Środkowo-Wschodniej jak i w populacjach pochodzenia indyjskiego. W Polsce wady klasy II są również najczęściej występującą wadą zgryzu.

Diagnostykę wad klasy II oraz różnicowanie wad szkieletowych i zębowych przeprowadza się na podstawie badania zewnątrzustnego, wewnątrzustnego, analizy modeli oraz badania radiologicznego w postaci analizy cefalometrycznej.

W badaniu zewnątrzustnym charakterystyczne cechy wskazujące na szkieletową wadę klasy II to cofnięta bródka, pogłębiona bruzda wagowo-bródkowa, cofnięta warga dolna. Często zaburzeniom przednio-tylnym towarzyszą też zaburzenia pionowe. Wewnątrzustnie oraz podczas analizy modeli można zauważyć pełną lub częściową klasę II wg Angle'a. W zależności od rodzaju wady może występować I lub II klasa kłowa, a siekacze górne mogą być wychylone, przechylone lub mogą mieć prawidłowa inklinację. Niedostateczny lub nadmierny wzrost szczęk zwykle w konsekwencji powoduje również nieprawidłowości w zgryzie. Diagnostykę wady w wymiarze strzałkowym i jej podłoże umożliwia analiza cefalometryczna, w której uwzględnia się szereg pomiarów, między innymi pomiar katów SNA, SNB oraz ANB, w celu określenia podłoża występującego zaburzenia. Określenie czynnika, najbardziej przyczyniającego się do powstania wady – zbyt dotylnej pozycji żuchwy lub/i wyrostka zębodołowego wraz z zębami żuchwy albo zbyt doprzedniej pozycji szczęki lub/i jej wyrostka zębodołowego wraz z uzębieniem – powinno warunkować zastosowanie odpowiedniej formy terapii. Najczęściej wykorzystywanym pomiarem jest kąt ANB, którego zwiększenie wskazuje na relację dotylną szczęk.

Leczenie wad klasy II jest uzależnione zarówno od przyczyny jak i wieku pacjentów. W trakcie wzrostu przeprowadza się najczęściej leczenie czynnościowe, które może wpłynąć na poprawę relacji szkieletowych. Natomiast w przypadku pacjentów dorosłych możliwe jest leczenie ortodontyczno-chirurgiczne lub kamuflaż wady. Leczenie kamuflujące wad klasy II/1 często wymaga ekstrakcji górnych przedtrzonowców oraz retrakcji segmentu zębów przednich – podobne postępowanie dotyczy leczenia również innych wad, takich jak: protruzji zębowo wyrostkowej czy dekompensacja przedoperacyjna wad klasy III . Efektem końcowym jest często nie tylko zmiana inklinacji oraz pozycji strzałkowej siekaczy, ale często również powikłanie w postaci niepożądanej resorpcji korzeni tych zębów oraz zmiana objętości wyrostka zębodołowego szczęki, a także dehiscencje.

Zastosowanie siły ortodontycznej powoduje naprężenia w obrębie więzadła przyzębia (PDL), które przekraczając ciśnienie krwi w tętniczkach włośniczkowych, powodują hialinizację, niedokrwienie i martwicę sąsiadujących tkanek, cementu korzeniowego i kości wyrostka zębodołowego. Komórki znajdujące się w pobliżu obszaru martwiczego mogą inicjować resorpcję korzenia. W związku z tym ustalono korelację pomiędzy nadmierną siłą ortodontyczną, skutkującą utrzymującym się wysokim poziomem stresu w PDL, upośledzonym przepływem krwi i indukowaną ortodontycznie resorpcją zapalną korzenia zęba (OIIRR). W dobie powszechnej dostępności badania CBCT z możliwością zastosowania TISAD, można dokładnie i indywidualnie przeanalizować anatomię każdego pacjenta, dopuszczając możliwość zastosowania retrakcji powyżej 7 mm. Zastosowanie retrakcji charakteryzuje się często dłuższym czasem leczenia, koniecznością zastosowania większych sił oraz przesunięciem zęba na większą odległość w porównaniu do innych strategii leczenia. Powyższe cechy mogą być przyczyną indukowanej ortodontycznie resorpcji zapalnej korzeni (OIIRR). Resorpcja korzenia zęba podczas leczenia ortodontycznego jest jednym z najczęstszych powikłań jatrogennych. Na to zjawisko składa się wiele czynników. W ostatnich latach, w wyniku rozwoju obrazowania 3D, zwrócono uwagę na kolejny ważny element, jakim jest kanał przysieczny i jego związek z korzeniami siekaczy górnych.

Kanał przysieczny, zwany także kanałem nosowo-podniebiennym, to połączenie między jamą nosową a jamą ustną, zawierające naczynia i nerwy. Jest to często pomijany element w procesie planowania leczenia ortodontycznego, a otoczony jest stosunkowo grubą płytką korową. Ocena i znajomość cech anatomicznych kanału przy siecznego, jego budowy, wielkości i zmian nachylenia w zależności od wieku, płci, a także parametrów decydujących o położeniu siekaczy szczęki może skutecznie zapobiegać poważnym powikłaniom leczenia ortodontycznego, takim jak resorpcja korzeni.

W praktyce klinicznej , w leczeniu aparatami stałymi cienkołukowymi stosuje się dwa rodzaje slotów zamków ortodontycznych: 0.018 i 0.022 cala. W zależności od zastosowanego slotu dobiera się odpowiednie rozmiary łuków stalowych, na których prowadzi się pożądany ruch ortodontyczny. Ponieważ celem leczenia ortodontycznego jest uzyskanie optymalnego ruchu zębów oraz poprawa profilu pacjenta, przy minimalnych efektach ubocznych, w przypadkach nasilonych wad konieczne jest dodatkowo zastosowanie miniimplantów ortodontycznych jako zakotwienia szkieletowego w celu uzyskania maksymalnej retrakcji siekaczy.

W wyniku przyłożonej siły ortodontycznej w ozębnej (periodontal ligament - PDL) pojawiają się naprężenia, które po stronie nacisku powodują resorpcję kości a po stronie rozciągania nawarstwianie nowej tkanki kostnej. Naprężenia, które przekraczają ciśnienie krwi w tętniczkach włosowatych powodują hialinizację związaną z niedokrwieniem i martwicą tkanek, przylegającego cementu korzeniowego i kości wyrostka zębodołowego. Komórki znajdujące się w blisko strefy martwicy mogą zainicjować resorpcję korzeni. W związku z tym wykryto związek pomiędzy zastosowaniem zbyt dużej siły ortodontycznej powodującej zbyt duże i stałe naprężenia w PDL i zahamowanie przepływu krwi a ortodontycznie indukowaną zapalną resorpcją korzeni zębów (OIIRR).

Z powyższych rozważań wynika, że w celu osiągnięcia optymalnych wyników leczenia konieczne jest przeprowadzenie precyzyjnej diagnostyki, zastosowanie optymalnej biomechaniki leczenia oraz uwzględnienie indywidualnych cech anatomii pacjenta w celu uniknięcia jatrogennych powikłań w czasie leczenia ortodontycznego.

Cel pracy:

1. Określenie wartości i dokładności diagnostyki cefalometrycznej wad w wymiarze strzałkowym.
2. Ocena wpływu różnych czynników na ryzyko resorpcji siekaczy górnych w wyniku kontaktu z blaszką kanału przysiecznego
3. Ocena biomechaniki retrakcji zębów górnych w aspekcie ryzyka wystąpienia resorpcji korzeni zębów siecznych oraz zmiany objętości kości wyrostka zębodołowego szczęki.

Materiał i metody:

Rozprawę doktorską stanowi cykl 7 publikacji o łącznym IF=25; MNiSW= 800 pkt. Jestem pierwszym autorem w 5 artykułach (artykuły nr 3, 4, 5, 6, 7), a drugim autorem w 2 artykułach (praca nr 1 i 2). Opublikowałam, w ramach cyklu: 4 przeglądy systematyczne(odpowiednio prace 1, 3, 4, 6) oraz 3 prace oryginalne (artykuły 2, 5 i 7).

W ramach cyklu na podstawie przeglądu systematycznego 1451 artykułów (praca 1) dokonałam analizy dostępnej wiedzy na temat dokładności różnych metod diagnostyki wad strzałkowych. Określiłam, na podstawie dostępnej wiedzy, skuteczność różnych pomiarów cefalometrycznych służących do określania pozycji podstaw szczęki i żuchwy w wymiarze wertykalnym i strzałkowym. Wykazałam, że diagnostyka ortodontyczna przy użyciu dotychczas stosowanych wskaźników antropometrycznych została wzbogacona o nowe kąty Tau, Yen, SAR, W, DW, Pi i analizę linijną Pi oceniające relacje sagitalne podstaw szczeki i żuchwy i wzbogacające złoty standard analizy w postaci kąta ANB. Określiłam również możliwość zastosowania nowych kąta R, płaszczyzny zewnątrzustnej KR oraz płaszczyzny górnej granicy łuku jarzmowego do oceny relacji wertykalnych. Na bazie dostępnej literatury wykazałam, że dotychczas używane w diagnostyce cefalometrycznej wskaźniki pomiarowe dla oceny relacji sagitalnej i wertykalnej utrzymują swoje zalety wobec umiarkowanych i słabych dowodów na jakość nowych wskaźników do ich oceny.

W pracy oryginalnej dokonałam samodzielnej weryfikacji zakresu, zależnego od lekarza, błędu pomiaru w dostępnych metodach analizy cefalometrycznej (praca 2: grupa badana 29. ortodontów). Zbadałam wiarygodność dwóch różnych metod pomiarów cefalometrycznych służących określaniu strzałkowej pozycji szczęki i żuchwy. Wykazałam, że uzyskane wyniki po zastosowaniu narzędzi statystycznych wskazują, że dyspersja poziomych współrzędnych punktów determinujących kąt ANB jest mniejsza niż w przypadku kąta tau, więc wartości kąta ANB cechują się mniejszym błędem pomiarowym niż wartości kąta tau. Wykazałam również po zastosowaniu współczynnika Kappa Cohena że kąt ANB nadal pozostaje podstawowym parametrem do diagnozowania szkieletowych zaburzeń strzałkowych, a upowszechnienie kąta tau wymaga wcześniejszego edukowania ortodontów.

W dwóch kolejnych przeglądach systematycznych zbadałam zakres dostępnej wiedzy na temat czynników mogących wpływać na biomechanikę retrakcji siekaczy szczęki (praca 3: 3175 artykułów, praca 4: 1401 artykułów). W pracy 3 dokonałam analizy dostępnej wiedzy dotyczącej metod kontrolowania pozycji siekaczy, podczas ich retrakcji w toku leczenia kamuflującego wad klasy II. Wykazałam, że dwustronna kortykotomia oraz zastosowanie miniimplantów do retrakcji en masse sa najlepszymi i skutecznymi metodami kontroli torku podczas retrakcji siekaczy w leczeniu ortodontycznym. W pracy 4 zbadałam zakres dostępnej wiedzy w zakresie charakterystyki remodelingu kości wyrostka zębodołowego w czasie retrakcji siekaczy szczęki. Analiza dostępnych publikacji wykazała, że w wyniku retrakcji siekaczy następuje znaczna utrata kości, co zmniejsza odległość między powierzchnią kości a powierzchnią korzenia od strony podniebiennej.

W kolejnej pracy oryginalnej (praca 5) dokonałam analizy biomechaniki retrakcji zębów szczęki w przypadkach ekstrakcyjnych i nieekstrakcyjnych za pomocą nowatorskiej metody nielinearnej analizy metodą elementów skończonych. W tej pracy określiłam wartość sił retrakcyjnych mogących skutkować przekroczeniem progu naprężeń optymalnych w więzadłach ozębnej. Przedstawiłam analizę naprężeń w ozębnej wykonaną metodą elementów skończonych, na nowatorskim, nielinearnym modelu szczęki, w trakcie retrakcji zębów górnych. W badaniu jako zmienne badane uwzględniono retrakcję en masse segmentu zębów górnych przednich do miniimplantu (TISAD) umieszczonego w okolicy pomiędzy drugim zębem przedtrzonowym a pierwszym trzonowym oraz dystalizację całego łuku również do TISAD przeprowadzoną na łuku 0.017*0.025 SS w zamkach slotu 0.018, z uwzględnieniem różnych wartości sił i wysokości haczyków wpływających na wektor zastosowanej siły. Wykazałam, że optymalnie łuki

0,017*0,025 SS w zamkach MBT 0,018 zapewniają doskonałą kontrolę torku, prowadząc do precyzyjnego osiowego przemieszczenia zębów, przy zastosowaniu optymalnych sił 180-200g/stronę nie ma ryzyka resorpcji wierzchołka korzenia.

Na podstawie dostępnej wiedzy, poprzez przegląd systematyczny 1862 artykułów (praca 6) określiłam ryzyko resorpcji siekaczy szczęki, w trakcie ich retrakcji, w związku z kontaktem z blaszką zbitą kanału przysiecznego. Określiłam obecny stan wiedzy na temat wpływu morfologii kanału przysiecznego na możliwość występowania resorpcji korzeni siekaczy górnych w trakcie ich retrakcji w toku leczenia kamuflującego wad klasy II. Wykazałam, że kontakt korzeni siekaczy z kanałem przysiecznym zwiększa ryzyko resorpcji tych korzeni.

Na tej podstawie zaplanowałam badanie oryginalne, opublikowane jako praca 7, w której dokonałam analizy badań CBCT 67 pacjentów. Dokonałam klasyfikacji morfologii kanału przysiecznego pacjentów, w zależności od wieku i płci. Na tej podstawie stworzyłam wykaz zaleceń dotyczących unikania ryzyka resorpcji korzeni siekaczy górnych w trakcie ich retrakcji, w związku z kontaktem ze ścianami kanału przysiecznego. Przeprowadzone przeze mnie badania wykazały różną szerokość kanału siecznego w zależności od płci.

Wyniki

W publikacji 1 na podstawie dostępnej literatury usystematyzowano dostępną wiedzę dotyczącą skuteczność różnych pomiarów cefalometrycznych służących do określania pozycji podstaw szczęki i żuchwy w wymiarze wertykalnym i sagitalnym. Wykazano, że diagnostyka ortodontyczna przy użyciu dotychczas stosowanych wskaźników antropometrycznych została wzbogacona o nowe kąty Tau, Yen, SAR, W, DW, Pi i analiza linijna Pi oceniające relacje sagitalne podstaw szczeki i żuchwy wzbogacające złoty standard analizy w postaci kąta ANB. Określono również możliwość zastosowania nowych pomiarów: kąta R, płaszczyzny zewnątrzustnej KR oraz płaszczyzny górnej granicy łuku jarzmowego do oceny relacji vertykalnych. Na bazie dostępnej literatury wykazano, że dotychczas używane w diagnostyce cefalometrycznej wskaźniki pomiarowe dla oceny relacji sagitalnej i wertykalnej utrzymują swoje zalety wobec umiarkowanych i słabych dowodów na jakość nowych wskaźników do ich oceny.

W pracy oryginalnej nr 2, dotyczącej porównania wiarygodności i powtarzalności pomiarów cefalometrycznych odnoszących się do dyskrepancji sagitalnej porównującej pomiary kąta ANB i kąta Tau uzyskano następujące wyniki:

Kąt ANB. Najwyższy współczynnik korelacji Pearsona stwierdzono w przypadku współrzędnych Ax i Ay. Błąd Dahlberga wahał się od 0,265 do 0,665, a współczynniki korelacji międzyklasowej i wewnątrzklasowej (ICC) mieściły się w przedziale od 0,841 do 1,000, wskazując na bardzo dużą zgodność pomiarów badaczy. Błąd powtarzalności (BP), błąd odtwarzalności wśród różnych lekarzy (BO), zmienność indywidualna pacjenta (ZI) oraz łączny błąd powtarzalności i odtwarzalności (R&R) wyniosły, odpowiednio: 1,61%, 0,92%, 97,47% oraz 2,53%.

Kąt tau. Najwyższy współczynnik korelacji Pearsona stwierdzono w przypadku współrzędnych poziomych Tx i Mx. Błąd Dahlberga wahał się od 0,891 do 1,639, a wartości ICC mieściły się w przedziale od 0,147 do 0,624, wskazując na słabą zgodność pomiarów badaczy. Wartości BP, BO, Zi oraz R&R wyniosły, odpowiednio: 4,30%, 3,94%, 91,76% oraz 8,24%.

Prawie cała zmienność wyników pomiarów kąta ANB i tau wynikała z wariancji międzygrupowej (zmienności indywidualnej pacjenta). Niska wartość R&R (poniżej 10%) oznacza, że oba kąty są dobrym parametrami diagnostycznymi wad strzałkowych

Ortodonci biorący udział w badaniu znacznie dokładniej mierzyli kąt ANB niż kąt tau: błąd Dahlberga i wartość R&R były około trzy razy większe, a wartość ICC – trzy i półkrotnie mniejsza w przypadku pomiarów kąta tau. Wyniki te wskazują, że dyspersja poziomych współrzędnych punktów determinujących kąt ANB jest mniejsza niż w przypadku kąta tau, więc wartości kąta ANB cechują się mniejszym błędem pomiarowym niż wartości kąta tau. Wartość kappa Cohena, czyli współczynnika rzetelności zastosowanego do oceny spójności ortodontów w kwestii ustalania klasy szkieletowej wyniosła 0,778 w przypadku kąta ANB i 0,722 w przypadku kąta tau, a analiza wyniku dowiodła statystycznej istotności różnicy ($p < 0,001$). Oznacza to, że kąt ANB nadal pozostaje podstawowym parametrem do diagnozowania szkieletowych zaburzeń strzałkowych, a upowszechnienie kąta tau wymaga wcześniejszego edukowania ortodontów.

W publikacji 3 we wszystkich badaniach podczas ruchu retrakcji obserwowano przechylenie siekaczy, czyli występował przedsionkowy tork korzenia zęba. W grupach leczonych średnia zmiana nachylenia policzkowo-podniebiennego korzeni siekaczy wyniosła 10,46. Biorąc pod uwagę wszystkie badania, średnia różnica w nachyleniu górnych siekaczy pomiędzy grupą kontrolną i leczoną wyniosła 2,46°, co było statystycznie istotne ($p = 0,0003$). Stosowanie kortykotomii podczas cofania zębów przednich znacznie zmniejsza nachylenie siekaczy szczęki, a kortykotomia może mieć znaczenie w kontroli nachylenia korzeni, tj. nacięcia należy wykonywać zarówno po stronie przedsionkowej, jak i podniebiennej. Stosowanie TISAD podczas retrakcji znacząco zmniejsza także przechylenie siekaczy szczęki. Przy cofaniu zębów przednich korzystniejsze jest zastosowanie mechaniki przedsionkowej niż językowej. Retrakcja masowa za pomocą miniimplantów i łuków po stronie przedsionkowej skutkuje zmniejszeniem nachylenia siekaczy szczęki w porównaniu z takim samym masowym ruchem z dostępu językowego i miniimplantami umieszczonymi na podniebieniu. Należy wspomnieć o zastosowaniu protokołów postępowania takich jak łuk intruzyjny czy system PASS podczas retrakcji siekaczy. Zastosowanie wyciągów klasy I skutkuje mniejszym nachyleniem siekaczy podczas retrakcji w porównaniu z zastosowaniem łańcuszka elastycznego.

W publikacji 4 po retrakcji siekaczy obserwuje się istotną statystycznie zmianę grubości kości. Po stronie podniebiennej obserwuje się znaczny ubytek kości. Zaobserwowana zmiana może zależeć zarówno od stopnia przesunięcia siekaczy, jak i zmiany ich nachylenia, a co za tym idzie, zmiany położenia wierzchołków korzeni. Zmiana ta jest znacznie większa u dorosłych niż u dorastającej młodzieży. Dodatkowo tempo retrakcji może skutkować większą utratą kości, ponieważ procesy naprawy mogą nie nadążać za procesami resorpcji. Zmiany w kościach strony wargowej budzą kontrowersje, gdyż wykazują zarówno zyski, jak i straty.

W pracy oryginalnej 5 podczas retrakcji en masse w spektrum przyłożonych sił od 50 g do 300 g wartości ciśnienia hydrostatycznego σh dla całego łuku zębowego wahają się od 0,37 kPa do 2,5 kPa. Warto zauważyć, że wartości ciśnienia σh wykazują liniową korelację ze wzrostem przyłożonej siły. Jednakże obserwuje się marginalne różnice w wartościach nacisku σh odpowiadające różnym wysokościom haczyków dla danej wielkości siły, które są nieistotne klinicznie. Warto zauważyć, że we wszystkich opisanych scenariuszach najniższy nacisk σh obserwuje się dla wysokości haka 6 mm, natomiast najwyższy dla wysokości haka 2 mm. Ciśnienie σh wywierane w ozębnej siekaczy centralnych waha się od 0,23 kPa do 1,54 kPa i wykazuje liniową zależność od przyłożonej siły. W odróżnieniu od całego łuku zębowego, minimalne wartości ciśnienia σh obserwuje się przy najniższej wysokości haka wynoszącej 2 mm, stopniowo narastając wraz ze wzrostem wysokości haka. We wszystkich przypadkach wartości nacisku σh wywieranego na siekacze centralne stanowią około 55% całkowitych wartości ciśnienia obserwowanych w obrębie przyzębia całego łuku zębowego. Ciśnienie σh w ozębnej siekaczy bocznych stanowi około 45% ciśnienia łuku pełnego i waha się od 0,18 kPa do 1,14 kPa przy rozkładzie liniowym. W odróżnieniu od całego łuku i siekaczy centralnych, najniższe wartości odnotowuje się przy najwyższej wysokości haka wynoszącej 10 mm i zwiększają się wraz ze zmniejszaniem się wysokości haka. W przypadku kłów wartości nacisków σh są największe i stanowią około 75% wartości całego ciśnienia w PDL pełnego łuku. Jego wartości wahają się od 0,28 do 1,83 kPa. Zależności są równoważne dla siekaczy bocznych. Wartość krytyczna 4,7 kPa zostaje przekroczona dla pełnego łuku zębowego przy działaniu siły 642 g i koncentruje się na górnych korzeniach pierwszych zębów trzonowych, osiągając jednocześnie w odcinku przednim 2,93 kPa, które kumuluje się głównie w prawym środkowym siekacz w okolicy dolnych połówek korzeni podniebiennych

W publikacji 6 we wszystkich artykułach skrócenie korzeni siekaczy górnych po retrakcji było statystycznie większe w przypadku kontaktu z kanałem przysiecznym. Aktualne publikacje zawarte w przeglądzie systematycznym wyraźnie wskazują na możliwe większe ryzyko resorpcji korzeni siekaczy podczas retrakcji oraz bocznego przemieszczenia lub intruzji po kontakcie z płytką korową kanału przysiecznego.

W pracy oryginalnej 7 stwierdzono wyraźną zależność pomiędzy szerokością kanału a jego długością AP. W większości grup wiekowych zwiększonej długości kanału towarzyszyła zwiększona szerokość na wszystkich poziomach (L1, L2 i L3). Ze względu na znacznie większą długość kanału na poziomie L1, ryzyko kontaktu szyjki z kanałem korzeniowym było wyższe u mężczyzn niż u kobiet. Badania u kobiet wykazały, że rozbieżność korzenia siekacza zwiększa się wraz ze wzrostem szerokości kanału, co wydaje się logiczne. Dla mężczyzn w wieku od 13 do 30 lat korelacja ta była ujemna, tj. im szerszy kanał, tym korzenie są bardziej równoległe lub zbieżne. Analiza nachylenia siekaczy i nachylenia kanału siecznego wykazała bardzo silną zależność, szczególnie w grupie wiekowej od 13 do 20 lat. U kobiet nachylenie kanału zwiększało się wraz ze wzrostem tylnego ruchu siekaczy, natomiast u mężczyzn sytuacja była odwrotna. Analiza szerokości kanału i odległości pomiędzy najbardziej mezjalnym punktem korzenia a styczną przechodzącą przez najbardziej wysunięty do przodu punkt kanału siecznego wykazała ujemną korelację we wszystkich grupach wiekowych mężczyzn. Im szerszy kanał, tym mniejsza odległość między korzeniami a kanałem.

Wnioski

1. Analiza porównawcza kąta ANB i kąta Tau w ocenie dyskrepancji sagitalnej potwierdziła, że kąt ANB nadal pozostaje podstawowym parametrem do diagnozowania szkieletowych zaburzeń strzałkowych, a upowszechnienie kąta tau wymaga wcześniejszego edukowania ortodontów. Powtarzalność oznaczania punktów pomiarowych oraz ocena indywidualnej koperty kostnej ma istotne znaczenie w aspekcie prawidłowej diagnostyki i doboru metody leczenia. Błąd ludzki może wpłynąć na sam proces pomiaru oraz na jego interpretację. W celu największej wiarygodności należy zidentyfikować najbardziej stabilne i powtarzalne punkty antropometryczne, niezależnie od kierunku wzrostu i zastosowanego leczenia ortodontycznego. Warto jednak pamiętać, że żadna metoda nie jest całkowicie wolna od błędów, a w niektórych sytuacjach uzyskane wyniki mogą wymagać walidacji metodą alternatywną. Badania skupiające się na analizie cefalometrycznej zazwyczaj koncentrują się na jednej grupie etniczne, co może prowadzić do błędnej interpretacji wyników. Zaś powtarzalność, oceniająca stopień w jakim pomiary wykonywane przez tego samego operatora

pokrywają się, i odtwarzalność, oceniająca pomiary wykonywane przez rożnych operatorów, mają kluczowe znaczenie dla dokładnej oceny zależności pomiędzy podstawą szczęki, wyrostkami zębodołowymi i zębami w zarówno w wymiarze strzałkowym, jak i pionowym. W przypadku nowego nieznanego i niewykonywanego dotychczas pomiaru istnieje wysokie ryzyko błędu ludzkiego. Błąd Dahlberga $p>0,1$ świadczy o konieczności nauczenia ortodontów oznaczania punktów antropometrycznych wchodzących w skład pomiaru.

2. Kontakt korzeni siekaczy z kanałem przysiecznym zwiększa ryzyko resorpcji tych korzeni. W diagnostyce ortodontycznej za pomocą obrazowania 3D należy uwzględnić anatomię układu IC, a ryzyko powikłań resorpcyjnych można zmniejszyć poprzez odpowiednie zaplanowanie zakresu przemieszczenia i torku korzeni siekaczy oraz ewentualne zastosowanie zamków siecznych z wbudowanym większym kątem. Istnieje zróżnicowanie szerokości kanału siecznego w zależności od płci. Długość przednio-tylna kanału w dużej mierze zależy od jego szerokości. Nachylenie kanału jest zależne od nachylenia siekaczy w różnych grupach wiekowych. Szerokość kanału zależy od zależnego od płci położenia zbieżnego lub rozbieżnego siekaczy. Blaszka zbita, która otacza kanał przysieczny jako pierwsza może przeszkadzać siekaczom podczas retrakcji, a także powodować ich resorpcję. Nasilone wychylenie siekaczy należy leczyć jak najwcześniej w okresie wzrostu młodzieńczego, kiedy zdolność organizmu do przebudowy jest duża i gdy wraz z kością następuje ruch ortodontyczny. W tym wieku kanał przysieczny, którego nachylenie zależne jest od nachylenia siekaczy, również może mieć większą zdolność do przebudowy. Znajomość anatomii kanału siecznego i zastosowanie obrazowania 3D u pacjentów wysokiego ryzyka może zapobiec resorpcji korzenia siekacza, uwzględniając indywidualne warunki anatomiczne pacjenta podczas planowania ortodontycznego przesuwania zębów.

3. Dwustronna kortykotomia oraz zastosowanie miniimplantów do retrakcji en masse sa najlepszymi i skutecznymi metodami kontroli torku podczas retrakcji siekaczy w leczeniu ortodontycznym. Zastosowanie zarówno mechaniki przedsionkowej, jak i dodatkowej rurki w zamkach umieszczonych na zębach trzonowych, co pozwala uzyskać efekt podobny do łuku intruzyjnego, badano w protokołach o niejasnym ryzyku błędu systematycznego, w których różne czynniki mogły mieć wpływ na wiarygodność wyników. Wiek pacjenta wydaje się nie mieć znaczenia dla kontroli torku. W wyniku retrakcji siekaczy następuje znaczna utrata kości, co zmniejsza odległość między powierzchnią kości a powierzchnią korzenia od strony podniebiennej. Wielkość tej zmiany może być różna, w zależności od stopnia przemieszczenia siekaczy i zmian w ich nachyleniu, co wpływa na położenie wierzchołków korzeni. Zmiana ta jest znacznie większa u dorosłych niż u dorastającej młodzieży. Uzasadnieniem tego

twierdzenia jest powszechnie znane zjawisko spadku aktywności komórkowej wraz z wiekiem. Zmniejszenie szybkości i intensywności zmian komórkowych może wyjaśniać zmniejszoną zdolność do przebudowy wraz ze wzrostem wieku pacjenta. Ruch ortodontyczny u dorosłych odbywa się poprzez kość i najczęściej kość nie dostosowuje się do nowego położenia zębów. Blaszkę korową podniebienną należy traktować jako nieuszkodzoną ścianę ograniczającą zakres planowanego ruchu siekaczy.

Łuki 0,017*0,025 SS w zamkach MBT 0,018 zapewniają doskonałą kontrolę torku, prowadząc do precyzyjnego osiowego przemieszczenia zębów, przy zastosowaniu optymalnych sił 180-200g/stronę nie ma ryzyka resorpcji wierzchołka korzenia dzięki równomiernemu rozłożeniu lekkiego i średniego ciśnienia hydrostatycznego σh w więzadle przyzębia (PDL). Przyłożenie potrójnych sił ortodontycznych (600-640 g/stronę) może zainicjować proces resorpcji poprzez zamknięcie naczyń włosowatych, natomiast próba wyrównania łuku zębowego przy znacznej rozbieżności zębowo-wyrostkowej może skutkować fenestracją płytki przedsionkowej wyrostka zębodołowego. Zaleca się stosowanie wysokiej jakości modeli nieliniowych do analizy elementów skończonych (FEA), aby zapewnić wiarygodne, porównywalne i realistyczne symulacje bardzo przypominające warunki w jamie ustnej.

4. Abstract

Introduction

Class II defects are prevalent in Caucasian populations of northern Europe, Central and Eastern Europe, as well as in populations of Indian origin. In Poland, class II malocclusions are also the most common.

The diagnosis of class II defects and the differentiation of skeletal and dental defects are conducted through extraoral and intraoral examinations, model analysis, and radiological examination in the form of cephalometric analysis.

During extraoral examination, characteristic features indicating a class II skeletal defect include a receding chin, a deepened submental furrow, and a retracted lower lip. Additionally, anterior-posterior disorders often coincide with vertical disorders. Intraorally and during model analysis, full or partial Angle class II malocclusions can be observed. Depending on the type of defect, canine class I or II may be present, and the upper incisors may be tipped, tilted, or have a normal inclination. Insufficient or excessive jaw growth typically results in bite irregularities. Cephalometric analysis enables the diagnosis of the defect in the sagittal dimension and its basis, considering measurements such as SNA, SNB, and ANB angles, to determine the underlying cause of the disorder. Identifying the primary factor contributing to the defect, whether it be a posterior position of the mandible and/or the alveolar process with the lower teeth, or an anterior position of the maxilla and/or its alveolar process with the teeth, guides the selection of appropriate therapy. The ANB angle is commonly utilized, with an increased angle indicating a posterior relationship of the jaws.

Treatment of class II defects is contingent upon both the cause and the patient's age. Functional treatment is typically administered during growth stages, aiming to improve skeletal relations. Conversely, adult patients may undergo orthodontic and surgical treatment or camouflage of the defect. Camouflaging treatment of class II/1 defects often involves the extraction of upper premolars and retraction of anterior teeth segments, akin to treatments for other defects such as dentoalveolar protrusion or preoperative decompensation of class III defects. The final outcome often encompasses changes in incisor inclination and sagittal position, along with potential complications such as root resorption of these teeth and alterations in the volume of the maxillary alveolar process, as well as dehiscence.

Orthodontic force application induces stress in the periodontal ligament (PDL), surpassing blood pressure in capillary arterioles, leading to hyalinization, ischemia, and necrosis of adjacent tissues, root cement, and alveolar bone. Cells adjacent to the necrotic area may initiate root resorption. Thus, a correlation exists between excessive orthodontic force, persistent stress in the PDL, impaired blood flow, and orthodontically induced inflammatory root resorption (OIIRR). With the advent of widespread availability of CBCT examination and the utilization of TISAD, meticulous analysis of individual patient anatomy is achievable, facilitating retraction exceeding 7 mm. However, retraction employment often entails longer treatment duration, necessitates greater forces, and involves tooth displacement over longer distances compared to alternative treatment strategies. These features may contribute to orthodontically induced inflammatory root resorption (OIIRR), one of the most common iatrogenic complications during orthodontic treatment. Many factors contribute to this phenomenon. In recent years, as a result of the development of 3D imaging, attention has been paid to another important element, which is the incisive canal and its relationship with the roots of the upper incisors.

The incisive canal, also called the nasopalatine canal, is a connection between the nasal cavity and the oral cavity, containing vessels and nerves. This is an often overlooked element in the orthodontic treatment planning process and is surrounded by a relatively thick cortical plate. Assessment and knowledge of the anatomical features of the incisal canal, its structure, size, and changes in inclination depending on age, gender, as well as parameters determining the position of the maxillary incisors can effectively prevent serious complications of orthodontic treatment, such as root resorption.

In clinical practice, two types of orthodontic bracket slots are used in the treatment with thin-arch fixed appliances: 0.018 and 0.022 inches. Depending on the slot used, appropriate sizes of steel arches are selected, on which the desired orthodontic movement is carried out. Since the goal of orthodontic treatment is to obtain optimal tooth movement and improve the patient's profile, with minimal side effects, in cases of severe defects, it is additionally necessary to use orthodontic mini-implants as skeletal anchorage to obtain maximum retraction of the incisors.

As a result of the applied orthodontic force, stresses appear in the periodontal ligament (PDL), which cause bone resorption on the pressure side and the accumulation of new bone tissue on the tension side. Stresses that exceed the blood pressure in the capillary arterioles cause hyalinization associated with ischemia and necrosis of tissues, adjacent root cement, and alveolar bone. Cells close to the necrotic zone can initiate root resorption. Therefore, a relationship was found between the use of excessive orthodontic force, causing persistently high stress in the PDL and inhibition of blood flow, and orthodontically induced inflammatory tooth root resorption (OIIRR).

The above considerations show that to achieve optimal treatment results, precise diagnostics, optimal treatment biomechanics, and consideration of individual patient anatomy are necessary to avoid iatrogenic complications during orthodontic treatment.

Objective of the work:

1. Determining the value and accuracy of cephalometric diagnosis of defects in the sagittal dimension.
2. Assessment of the impact of various factors on the risk of resorption of the upper incisors as a result of contact with the lamina of the incisive canal.
3. Assessment of the biomechanics of upper tooth retraction in terms of the risk of resorption of the roots of incisors and changes in the volume of the maxillary alveolar bone.

Materials and Methods:

The doctoral dissertation comprises a series of seven publications with a cumulative Impact Factor (IF) of 25 and 800 points awarded by the Ministry of Science and Higher Education. I am the first author on five of these articles (articles 3, 4, 5, 6, and 7) and the second author on two articles (papers 1 and 2). The series includes four systematic reviews (papers 1, 3, 4, and 6) and three original research papers (articles 2, 5, and 7).

In this series, I conducted a systematic review of 1,451 articles (paper 1) to analyze the current knowledge on the accuracy of various methods for diagnosing sagittal defects. Utilizing this knowledge, I assessed the effectiveness of various cephalometric measurements in determining the positions of the maxilla and mandible bases in both the vertical and sagittal dimensions. My research demonstrated that orthodontic diagnostics, which traditionally relied on anthropometric indices, could be enhanced with new angles such as Tau, Yen, SAR, W, DW, Pi, and linear analysis Pi. These new measures supplement the gold standard ANB angle in assessing the sagittal relations of the maxillary and mandibular bases. Additionally, I explored the potential use of new angles R, the extraoral plane KR, and the plane of the upper border of the zygomatic arch to evaluate vertical relationships. My findings indicated that the traditional measurement indices used in cephalometric diagnostics for sagittal and vertical relationships maintain their advantages, whereas the quality of evidence for the new indices is moderate to weak.

In my original research, I independently verified the measurement error scope in existing cephalometric analysis methods, depending on the orthodontist (paper 2: study group of 29 orthodontists). I assessed the reliability of two different cephalometric measurement methods for determining the sagittal positions of the maxilla and mandible. Statistical analysis revealed that the dispersion of horizontal coordinates for points determining the ANB angle is smaller than that for the Tau angle, indicating that the ANB angle has a smaller measurement error. Additionally, using Cohen's Kappa coefficient, I demonstrated that the ANB angle remains the primary parameter for diagnosing skeletal sagittal disorders. The adoption of the Tau angle in clinical practice requires prior education and training of orthodontists.

In two subsequent systematic reviews, I examined the scope of available knowledge on factors that may influence the biomechanics of maxillary incisor retraction (paper 3: 3,175 articles; paper 4: 1,401 articles). In paper 3, I analyzed the existing knowledge regarding methods of controlling the position of the incisors during their retraction in the camouflaging treatment of Class II defects. I demonstrated that bilateral corticotomy and the use of mini-implants for en-masse retraction are the most effective methods of torque control during incisor retraction in orthodontic treatment. In paper 4, I explored the characteristics of alveolar bone remodeling during maxillary incisor retraction. The analysis of the available literature revealed that significant bone loss occurs as a result of incisor retraction, reducing the distance between the bone surface and the root surface on the palatal side.

In another original work (paper 5), I analyzed the biomechanics of maxillary tooth retraction in both extraction and non-extraction cases using an innovative non-linear finite element analysis method. In this study, I determined the retraction force values that may exceed the optimal stress threshold in the periodontal ligament. I conducted a stress analysis in the periodontium using the finite element method on an innovative, non-linear model of the jaw during upper tooth retraction. The study variables included en masse retraction of a segment of the upper front teeth to a mini-implant (TISAD) placed between the second premolar and the first molar, and distalization of the entire arch also to TISAD, performed on a 0.017 × 0.025 SS archwire in 0.018 slot brackets. Various force values and hook heights influencing the applied force vector were considered. I showed that optimal 0.017 × 0.025 SS archwires in MBT 0.018 brackets provide excellent torque control, leading to precise axial displacement of the teeth. With the use of optimal forces of 180-200g per side, there is no risk of root apex resorption.

Based on a systematic review of 1,862 articles (paper 6), I assessed the risk of resorption of the maxillary incisors during retraction due to contact with the compact lamina of the incisive canal. I evaluated the current state of knowledge on the influence of the morphology of the incisive canal on the risk of resorption of the roots of the upper incisors during retraction in the camouflaging treatment of Class II defects. I found that contact of the incisor roots with the incisive canal increases the risk of root resorption.

Subsequently, I planned an original study, published as paper 7, in which I analyzed CBCT examinations of 67 patients. I classified the morphology of the incisive canal according to age and gender. Based on these findings, I developed a list of recommendations to avoid the risk of resorption of the roots of the upper incisors during retraction due to contact with the walls of the incisive canal. My research demonstrated varying widths of the incisive canal depending on gender.

Results

Publication 1 systematized the available knowledge regarding the effectiveness of various cephalometric measurements used to determine the position of the maxillary and mandibular bases in the vertical and sagittal dimensions. It was demonstrated that orthodontic diagnostics, previously reliant on traditional anthropometric indices, have been enhanced with new angles such as Tau, Yen, SAR, W, DW, and Pi, along with linear Pi analysis for assessing sagittal relationships of the maxillary and mandibular bases. These additions enrich the gold standard of analysis, which includes the ANB angle. The study also identified the potential use of new measurements—the R angle, the extraoral KR plane, and the plane of the upper border of the zygomatic arch—for assessing vertical relations. Despite moderate and weak evidence supporting the quality of these new indices, traditional measurement indices in cephalometric diagnostics for sagittal and vertical relationship assessment maintain their advantages.

Original Paper 2 focused on comparing the reliability and repeatability of cephalometric measurements related to sagittal discrepancy by comparing the ANB angle and the Tau angle. The following results were obtained:

ANB Angle: The highest Pearson correlation coefficient was found for the Ax and Ay coordinates. The Dahlberg error ranged from 0.265 to 0.665, and the interclass and intraclass correlation coefficients (ICC) ranged from 0.841 to 1.000, indicating very high agreement between researchers' measurements. The repeatability error (BP), inter-physician reproducibility error (BO), individual patient variability (ZI), and total repeatability and reproducibility error (R&R) were 1.61%, 0.92%, 97.47%, and 2.53%, respectively.

Tau Angle: The highest Pearson correlation coefficient was found for the horizontal Tx and Mx coordinates. The Dahlberg error ranged from 0.891 to 1.639, and the ICC values ranged from 0.147 to 0.624, indicating poor agreement between researchers' measurements. The BP, BO, ZI, and R&R values were 4.30%, 3.94%, 91.76%, and 8.24%, respectively.

Almost all of the variability in ANB and Tau measurements was due to between-group variance (individual patient variability). A low R&R value (below 10%) indicates that both angles are good diagnostic parameters for sagittal discrepancies. The orthodontists in the study measured the ANB angle much more accurately than the Tau angle: the Dahlberg error and R&R were approximately three times greater, and the ICC was three and a half times lower for Tau angle measurements. These results indicate that the dispersion of the horizontal coordinates of the points determining the ANB angle is smaller than that for the Tau angle, resulting in a smaller measurement error for the ANB angle. The value of Cohen's kappa, the reliability coefficient used to assess the consistency of orthodontists in determining the skeletal class, was 0.778 for the ANB angle and 0.722 for the Tau angle. The analysis of these results proved the statistical significance of the difference ($p < 0.001$). This means that the ANB angle remains the primary parameter for diagnosing skeletal sagittal disorders, and the popularization of the Tau angle requires prior education of orthodontists.

In Publication 3, all tests demonstrated tilting of the incisors during retraction movements, specifically showing vestibular torque of the tooth root. In the treated groups, the average change in the buccopalatal inclination of the incisor roots was 10.46°. Across all studies, the mean difference in the inclination of the upper incisors between the control and treatment groups was 2.46°, which was statistically significant ($p = 0.0003$). The use of corticotomy significantly reduces the inclination of the maxillary incisors during retraction, suggesting that corticotomy may be crucial for controlling root inclination; this involves making incisions on both the vestibular and palatal sides. Additionally, the use of temporary anchorage devices (TISAD) during retraction significantly reduces the tilt of the maxillary incisors. When retracting anterior teeth, vestibular mechanics are more advantageous than lingual mechanics. Mass retraction using mini-implants and arches on the vestibular side results in less inclination of the maxillary incisors compared to using the lingual approach with mini-implants placed on the palate. Notably, treatment protocols such as the intrusion arch or the PASS system during incisor retraction, as well as using Class I tractions, result in less inclination compared to the use of an elastic chain.

Publication 4 reports a statistically significant change in bone thickness following incisor retraction, with significant bone loss observed on the palatal side. This change may be influenced by both the degree of incisor displacement and the change in their inclination, which affects the position of the root tips. The change is significantly greater in adults compared to adolescents. Additionally, the rate of retraction can lead to greater bone loss, as reparative processes may not keep pace with resorption. Changes in the bone on the labial side are controversial, with observations of both gains and losses.

In **Original Work 5,** during en masse retraction with applied forces ranging from 50 g to 300 g, hydrostatic pressure (σh) values for the entire dental arch ranged from 0.37 kPa to 2.5 kPa, demonstrating a linear correlation with the increase in applied force. Differences in σh values corresponding to different hook heights for a given force magnitude were clinically insignificant. The lowest pressure σh was observed at a hook height of 6 mm, while the highest was at 2 mm. The σh pressure in the periodontium of the central incisors ranged from 0.23 kPa to 1.54 kPa, also showing a linear dependence on the applied force. Unlike the entire dental arch, the minimum σh values for the central incisors were observed at the lowest hook height of 2 mm, increasing with greater hook heights. In all cases, the σh pressure on the central incisors constituted approximately 55% of the total pressure observed in the periodontium of the entire dental arch. For the lateral incisors, the σh pressure was approximately 45% of the full arch pressure, ranging from 0.18 kPa to 1.14 kPa with a linear distribution. The lowest values for the lateral incisors were recorded at the highest hook height of 10 mm, increasing as the hook height decreased. For canines, the σh pressure values were the highest, constituting about 75% of the total pressure in the PDL of the full arch, ranging from 0.28 to 1.83 kPa, with relationships similar to those of the lateral incisors. The critical value of 4.7 kPa was exceeded for a full dental arch with a force of 642 g, concentrating on the upper roots of the first molars, while reaching 2.93 kPa in the anterior section, predominantly in the area of the lower halves of the palatal roots of the right central incisor.

In Publication 6, all articles reported that the shortening of the roots of the upper incisors after retraction was statistically greater when there was contact with the incisive canal. Current publications included in the systematic review clearly indicate a higher risk of incisor root resorption during retraction and lateral displacement or intrusion after contact with the cortical plate of the incisive canal.

In the original work 7, a clear relationship was found between the canal width and its anteroposterior (AP) length. In most age groups, increased canal length was accompanied by increased width at all levels (L1, L2, and L3). Due to the significantly greater length of the canal at the L1 level, the risk of cervical contact with the root canal was higher in men than in women. Studies in women have shown that incisor root divergence increases with increasing canal width, which is logical. For men aged 13 to 30, this correlation was negative; the wider the canal, the more parallel or convergent the roots were. The analysis of the inclination of the incisors and the inclination of the incisive canal showed a very strong relationship, especially in the age group from 13 to 20 years. In women, canal inclination increased with the posterior movement of the incisors, while in men the situation was the opposite. Analysis of the canal width and the distance between the most mesial point of the root and the tangent passing through the most forward point of the incisive canal showed a negative correlation in all age groups of men. The wider the canal, the smaller the distance between the roots and the canal.

Conclusions

1. The comparative analysis of the ANB angle and the Tau angle in the assessment of sagittal discrepancy confirmed that the ANB angle remains the basic parameter for diagnosing skeletal sagittal disorders. The popularization of the Tau angle requires prior education of orthodontists. The repeatability of marking measurement points and the assessment of the individual bone envelope are important for correct diagnosis and selection of treatment methods. Human error may affect the measurement process and its interpretation. For maximum reliability, the most stable and repeatable anthropometric points should be identified, regardless of the direction of growth and orthodontic treatment used. However, it is important to remember that no method is completely error-free, and in some situations, the results obtained may require validation with an alternative method.
Studies focusing on cephalometric analysis usually focus on one ethnic group, which may lead to misinterpretation of the results. Repeatability, assessing the degree to which measurements performed by the same operator overlap, and reproducibility, assessing measurements performed by different operators, are crucial for accurately assessing the relationship between the jaw base, alveolar ridges, and teeth in both the sagittal and vertical dimensions. In the case of a new, unknown, and previously unperformed measurement, there is a high risk of human error. A Dahlberg error greater than 0.1 indicates the need to teach orthodontists how to mark anthropometric points included in the measurement.

2. Contact between the incisor roots and the incisive canal increases the risk of root resorption. When conducting orthodontic diagnostics using 3D imaging, the anatomy of the incisive canal

system should be considered. The risk of resorption complications can be minimized by carefully planning the extent of displacement and torque of the incisor roots and potentially using incisal brackets with a built-in larger angle. The width of the incisive canal varies by gender, with the anteroposterior length of the canal largely dependent on its width. The inclination of the canal correlates with the inclination of the incisors across different age groups. The width of the canal is influenced by the sex-dependent position of convergent or divergent incisors. The lamina compacta surrounding the incisive canal is the first to interfere with the incisors during retraction, potentially causing resorption. Severe inclination of the incisors should be addressed as early as possible during adolescence, a period of high remodeling capacity and orthodontic movement alongside bone growth. At this stage, the incisive canal, whose inclination is affected by the incisors, may also have a greater capacity for reconstruction. Understanding the anatomy of the incisive canal and utilizing 3D imaging in high-risk patients can prevent incisor root resorption by considering individual anatomical conditions when planning orthodontic tooth movements.

3. Bilateral corticotomy and the use of mini-implants for en masse retraction are effective methods for torque control during incisor retraction in orthodontic treatment. The application of vestibular mechanics and an additional tube in molar brackets, providing effects similar to an intrusion archwire, has been examined in studies with potential bias due to various influencing factors. The patient's age does not significantly impact torque control. Significant bone loss occurs during incisor retraction, reducing the distance between the bone surface and the root surface on the palatal side. The extent of this change varies with the degree of incisor displacement and inclination, affecting the position of the root tips. This change is more pronounced in adults than in adolescents, explained by the decline in cellular activity with age. The decreased rate and intensity of cellular changes in adults may account for the reduced capacity for remodeling as they age. In adults, orthodontic movement occurs through the bone, which often does not adapt to the new tooth positions. The palatine cortical plate should be treated as an undamaged barrier limiting the range of planned incisor movements.

The use of 0.017*0.025 SS archwires in MBT 0.018 brackets provides excellent torque control, leading to precise axial displacement of teeth. When optimal forces of 180-200g/side are applied, there is no risk of root apex resorption due to the even distribution of light and medium hydrostatic pressure (σh) in the periodontal ligament (PDL). However, applying triple orthodontic forces (600-640 g/side) may initiate the resorption process by occluding the capillaries, and attempting to align the dental arch with significant dento-alveolar discrepancies may result in fenestration of the vestibular plate of the alveolar process. The use of high-quality nonlinear finite element analysis (FEA) models is recommended to provide reliable, comparable, and realistic simulations that closely resemble oral conditions.

5. Wprowadzenie

Wady klasy II dominują zarówno w populacjach kaukaskich Europy północnej, środkowo-wschodniej jak i w populacjach pochodzenia indyjskiego[1]. W Polsce wady klasy II są również najczęściej występującą wadą zgryzu, przy czym dominuje podtyp związany z protruzją siekaczy górnych. Na drugim miejscu są wady poprzeczne w postaci zgryzów krzyżowych. Częstość występowania wad zgryzu rośnie też z wiekiem[2].

Diagnostykę wad klasy II oraz różnicowanie wad szkieletowych i zębowych przeprowadza się na podstawie badania zewnątrzustnego, wewnątrzustnego, analizy modeli oraz badania radiologicznego w postaci analizy cefalometrycznej. Przyczyną wad klasy II może być retrognatyczna żuchwa, prognatyczna szczęka lub połączenie ich obu. Podłoże może mieć charakter morfologiczny lub czynnościowy.

W badaniu zewnątrzustnym charakterystyczne cechy wskazujące na szkieletową wadę klasy II to cofnięta bródka, pogłębiona bruzda wagowo-bródkowa, cofnięta warga dolna. Często zaburzeniom przednio-tylnym towarzyszą też zaburzenia pionowe. Wewnątrzustnie oraz podczas analizy modeli można zauważyć pełną lub częściową klasę II wg Angle'a. Klasa II wg Angle'a określa takie położenie łuków zębowych, w których dolny trzonowiec ustawiony jest dotylnie w stosunku do górnego. W zależności od rodzaju wady może występować I lub II klasa kłowa, a siekacze górne mogą być wychylone, przechylone lub mogą mieć prawidłowa inklinację, co jest dodatkowo określane jako podtyp II/1 lub II/2. Niedostateczny lub nadmierny wzrost szczęk zwykle w konsekwencji powoduje również nieprawidłowości w zgryzie. Diagnostykę wady w wymiarze strzałkowym i jej podłoże umożliwia analiza cefalometryczna, w której uwzględnia się szereg pomiarów, między innymi pomiar katów SNA, SNB oraz ANB, w celu określenia podłoża występującego zaburzenia. Określenie czynnika, najbardziej przyczyniającego się do powstania wady – zbyt dotylnej pozycji żuchwy lub/i wyrostka zębodołowego wraz z zębami żuchwy albo zbyt doprzedniej pozycji szczęki lub/i jej wyrostka zębodołowego wraz z uzębieniem – powinno warunkować zastosowanie odpowiedniej formy terapii [3]. Najczęściej wykonywanym pomiarem jest kąt ANB, którego zwiększenie wskazuje na relację dotylną szczek. Dodatkowo takie parametry jak WITZ, kąty Tau, Yen, SAR, W, DW, Pi i analiza linijna Pi oceniają relacje sagitalne podstaw szczeki i żuchwy oraz wzbogacają złoty standard analizy w postaci kąta ANB. Na dokładność pomiarów wpływają pewne parametry takie jak powtarzalność i łatwość określania poszczególnych punktów oraz odmienności anatomiczne struktur twarzoczaszki oraz ich wzrost. Są one związane między innymi: ze stabilnością kąta ANB na skutek zmian wzrostu oraz niestabilnością położenia punktu N, co ma wpływ na wielkość i klarowność kąta ANB podczas wzrostu; zmianami w pomiarze długości podstawy czaszki, które również wpływają na kąt ANB; rotacją kłykcia w stawie skroniowo-żuchwowym, która wpływa na zmiany relacji strzałkowej podstaw szczęki względem siebie oraz rotację żuchwy podczas leczenia ortodontycznego; oceną WITS, która jest związana z niestabilnością płaszczyzny zgryzowej; oceną kąta W, mierzonego pomiędzy prostą prostopadłą do punktu M na prostej SG a prostą MG, w którym wykorzystuje się punkty M i G, które są stosunkowo stabilne i nie ulegają relokacji na skutek przebudowy związanej z ruchami zębów, to punkt S jest natomiast wysoce niestabilny, ponieważ podczas wzrostu porusza się do tyłu i w dół; niedokładnością i trudnością wyznaczenia kąta Beta, który wykorzystuje trzy charakterystyczne elementy szkieletu – punkt A, punkt B i wydatną oś kłykciową - analiza kąta beta opiera się na punkcie A jako punkcie orientacyjnym, a zmiany jego położenia wiążą się z przebudową zębodołu wynikającą z ruchów ortodontycznych a dodatkowo określenie położenia kłykcia żuchwy może być trudne, co w konsekwencji ogranicza wiarygodność kąta Beta; oceną kąta YEN opierającego się na punktach orientacyjnych S, M (środek przedniej części szczęki) i G (środek w dolnej części spojenia), które razem tworzą kąt YEN mierzony w punkcie M - niedokładność wynika z faktu, że punkt G w trakcie wzrostu przesuwa się w sposób przypominający literę „S”[4].

Leczenie wad klasy II jest uzależnione zarówno od przyczyny jak i wieku pacjentów. W trakcie wzrostu przeprowadza się najczęściej leczenie czynnościowe, które może wpłynąć na poprawę relacji szkieletowych. Natomiast w przypadku pacjentów dorosłych możliwe jest leczenie ortodontyczno-chirurgiczne lub kamuflaż wady. Leczenie kamuflujące wad klasy II/1 często wymagają ekstrakcji górnych przedtrzonowców oraz retrakcji segmentu zębów przednich – podobne postępowanie dotyczy leczenia również innych wad, takich jak: protruzji zębowo wyrostkowej czy dekompensacja przedoperacyjna wad klasy III . W trakcie tego etapu może nastąpić osiowe cofanie zębów, ich kontrolowane lub niekontrolowane nachylanie. Efektem końcowym jest nie tylko zmiana inklinacji oraz pozycji strzałkowej siekaczy, ale często powikłanie w postaci niepożądanej resorpcji korzeni tych zębów oraz zmiana objętości wyrostka zębodołowego szczęki, a także dehiscencje.

Zastosowanie siły ortodontycznej powoduje naprężenia w obrębie więzadła przyzębia (PDL), które przekraczając ciśnienie krwi w tętniczkach włośniczkowych, powodują hialinizację, niedokrwienie i martwicę sąsiadujących tkanek, cementu korzeniowego i kości wyrostka zębodołowego. Komórki znajdujące się w pobliżu obszaru martwiczego mogą inicjować resorpcję korzenia[5]. W związku z tym ustalono korelację pomiędzy nadmierną siłą ortodontyczną, skutkującą utrzymującym się wysokim poziomem stresu w PDL, upośledzonym przepływem krwi i indukowaną ortodontycznie resorpcją zapalną korzenia zęba (OIIRR)[6]. Jednakże dokładne przyczyny OIIRR pozostają nie do końca wyjaśnione. Jego etiologia jest szczególnie złożona i nie do końca poznana. Oprócz wspomnianych powyżej nadmiernych sił ortodontycznych, na szereg czynników wpływających składają się predyspozycje genetyczne, czas trwania leczenia ortodontycznego, stopień przemieszczenia zęba oraz charakter zastosowanej siły, zarówno ciągłej, jak i przerywanej. Granica maksymalnej retrakcji siekaczy jest od lat przedmiotem dyskusji. Przyjętym standardem, zgodnie z zakresem rozbieżności ustalonym przez Profitta i Ackermana w 1994 roku, jest możliwość retrakcji górnych siekaczy o około 7 mm[3]. Określenie tych wymiarów przeprowadzono na podstawie radiogramów 2D i obecności płytki korowej. W dobie powszechnej dostępności badania CBCT z możliwością zastosowania TISAD, można dokładnie i indywidualnie przeanalizować anatomię każdego pacjenta, dopuszczając możliwość zastosowania retrakcji powyżej 7 mm[7]. Zastosowanie retrakcji charakteryzuje się dłuższym czasem leczenia, zastosowaniem większych sił oraz przesunięciem zęba na większą odległość w porównaniu do innych strategii leczenia. Uważa się, że wszystkie powyższe cechy mogą być przyczyną OIIRR[8,9]. Resorpcja korzenia zęba podczas leczenia ortodontycznego jest jednym z najczęstszych powikłań jatrogennych[8]. W ostatnich latach, w wyniku rozwoju obrazowania 3D, zwrócono uwagę na kolejny ważny element, jakim jest kanał przysieczny i jego związek z korzeniami siekaczy górnych.

Kanał przysieczny, zwany także kanałem nosowo-podniebiennym, to połączenie między jamą nosową a jamą ustną, zawierające naczynia i nerwy. Jest to często pomijany element w procesie planowania leczenia ortodontycznego, a otoczony jest stosunkowo grubą płytką korową[10,11]. Ponieważ istnieją dowody na wpływ płytki korowej policzkowej i podniebiennej na indukcję resorpcji korzenia, analogicznym czynnikiem może być płytka korowa kanału siecznego. Kanał przysieczny służy jako połączenie między jamą ustną i nosową. Kończy się w jamie ustnej w dole siecznym, poniżej brodawki przysiecznej, bezpośrednio za górnymi siekaczami środkowymi. Jest otoczony z każdej strony grubą kością korową i zawiera nerwy i naczynia zaopatrujące górne siekacze i przednią część podniebienia. Ocena i znajomość cech anatomicznych kanału przysiecznego, jego budowy, wielkości i zmian nachylenia w zależności od wieku, płci, a także parametrów decydujących o położeniu siekaczy szczęki może skutecznie zapobiegać poważnym powikłaniom leczenia ortodontycznego, takim jak resorpcja korzeni. Wymagają one dalszych badań ze względu na niedostateczną ocenę tego obszaru na rutynowo wykonywanych zdjęciach panoramicznych i cefalometrycznych. Natomiast dokładna kontrola torku zapobiegająca nadmiernemu przychyleniu siekaczy górnych oraz spersonalizowane planowanie położenia siekaczy w istniejącej kopercie kostnej są niezbędne dla zachowania zdrowych korzeni.

W praktyce klinicznej, w leczeniu aparatami stałymi cienkołukowymi stosuje się dwa rodzaje slotów zamków ortodontycznych: 0.018 i 0.022 cala. W zależności od zastosowanego slotu dobiera się odpowiednie rozmiary łuków stalowych, na których prowadzi się pożądany ruch ortodontyczny. Ponieważ celem leczenia ortodontycznego jest uzyskanie optymalnego ruchu zębów oraz poprawa profilu pacjenta, przy minimalnych efektach ubocznych, w przypadkach nasilonych wad konieczne jest dodatkowo zastosowanie miniimplantów ortodontycznych jako zakotwienia szkieletowego w celu uzyskania maksymalnej retrakcji siekaczy. Kombinacja zastosowanych zamków, łuków, wektorów i wartości sił oraz metod ortodontycznych w połączeniu z anatomią wyrostka zębodołowego szczęki ma przełożenie na ruch ortodontyczny oraz ewentualne działania niepożądane w postaci nadmiernego przechylenia siekaczy, kontaktu z blaszką zbitą lub resorpcji korzeni głównie siekaczy górnych.

W wyniku przyłożonej siły ortodontycznej w periodontal ligament (PDL) pojawiają się naprężenia, które po stronie nacisku powodują resorpcję kości a po stronie rozciągania nawarstwianie nowej tkanki kostnej. Naprężenia, które przekraczają ciśnienie krwi w tętniczkach włosowatych powodują hialinizację związaną z niedokrwieniem i martwicą tkanek, przylegającego cementu korzeniowego i kości wyrostka zębodołowego. Komórki znajdujące się w blisko strefy martwicy mogą zainicjować resorpcję korzeni. W związku z tym wykryto związek pomiędzy zastosowaniem zbyt dużej siły ortodontycznej powodującej zbyt duże i stałe naprężenia w PDL i zahamowanie przepływu krwi a ortodontycznie indukowaną zapalną resorpcją korzeni zębów (OIIRR)[6]. Wartości ciśnienia hydrostatycznego w PDL wynikające z zastosowanego leczenia ortodontycznego oraz jego rozkład na korzeniach nie są możliwe do zmierzenia w warunkach klinicznych. Mogą być jednak ocenione na podstawie analizy modelu metodą elementów skończonych (FEM). Pozwala ona zasymulować złożone sytuacje naprężeń mechanicznych w obszarze szczeki, wyrostka zębodołowego i zębów. Analiza wyników może wykazać, które obciążenia i w jakich lokalizacjach mogą przekraczać ciśnienie panujące w naczyniach krwionośnych ozębnej i skutkować powikłaniem w postaci resorpcji korzeni.

Z powyższych rozważań wynika, że w celu osiągnięcia optymalnych wyników leczenia konieczne jest przeprowadzenie precyzyjnej diagnostyki, zastosowanie optymalnej biomechaniki leczenia oraz uwzględnienie indywidualnych cech anatomii pacjenta w celu uniknięcia jatrogennych powikłań w czasie leczenia ortodontycznego.

6. Założenia i cele pracy

Celem pracy doktorskiej było określenie powikłań w trakcie leczenia wad wymiarze strzałkowym, a w szczególności:

1. Określenie wartości i dokładności diagnostyki cefalometrycznej wad w wymiarze strzałkowym.
2. Ocena wpływu różnych czynników na ryzyko resorpcji siekaczy górnych w wyniku kontaktu z blaszką kanału przysiecznego
3. Ocena biomechaniki retrakcji zębów górnych w aspekcie ryzyka wystąpienia resorpcji korzeni zębów siecznych oraz zmiany objętości kości wyrostka zębodołowego szczęki.

Założone cele badawcze zrealizowano poprzez przeprowadzenie 3 projektów badawczych oraz 4 przeglądów systematycznych, a każde z badań stanowiło podstawę do artykułu współtworzącego cykl.

7. Materiał i metody

W ramach cyklu, na podstawie przeglądu systematycznego 1451 artykułów (praca 1), dokonałam analizy dostępnej wiedzy na temat dokładności różnych metod diagnostyki wad strzałkowych. Określiłam, na podstawie dostępnej wiedzy, skuteczność różnych pomiarów cefalometrycznych służących do określania pozycji podstaw szczęki i żuchwy w wymiarze wertykalnym i strzałkowym. Wykazałam, że diagnostyka ortodontyczna przy użyciu dotychczas stosowanych wskaźników antropometrycznych została wzbogacona o nowe kąty Tau, Yen, SAR, W, DW, Pi i analiza linijna Pi oceniające relacje sagitalne podstaw szczeki i żuchwy wzbogacające złoty standard analizy w postaci kąta ANB. Określiłam również możliwość zastosowania nowych kąta R, płaszczyzny zewnątrzustnej KR oraz płaszczyzny górnej granicy łuku jarzmowego do oceny relacji wertykalnych. Na bazie dostępnej literatury wykazałam, że dotychczas używane w diagnostyce cefalometrycznej wskaźniki pomiarowe dla oceny relacji sagitalnej i wertykalnej utrzymują swoje zalety wobec umiarkowanych i słabych dowodów na jakość nowych wskaźników do ich oceny.

W pracy oryginalnej dokonałam samodzielnej weryfikacji zakresu, zależnego od lekarza, błędu pomiaru w dostępnych metodach analizy cefalometrycznej (praca 2: analiza przeprowadzona przez 29 ortodontów). Zbadałam wiarygodność dwóch różnych metod pomiarów cefalometrycznych służących określaniu strzałkowej pozycji szczęki i żuchwy. Wykazałam, że uzyskane wyniki po zastosowaniu narzędzi statystycznych wskazują, że dyspersja poziomych współrzędnych punktów determinujących kąt ANB jest mniejsza niż w przypadku kąta tau, więc wartości kąta ANB cechują się mniejszym błędem pomiarowym niż wartości kąta tau. Wykazałam również po zastosowaniu współczynnika Kappa Cohena że kąt ANB nadal pozostaje podstawowym parametrem do diagnozowania szkieletowych zaburzeń strzałkowych, a upowszechnienie kąta tau wymaga wcześniejszego edukowania ortodontów.

W dwóch kolejnych przeglądach systematycznych zbadałam zakres dostępnej wiedzy na temat czynników mogących wpływać na biomechanikę retrakcji siekaczy szczęki (praca 3: 3175 artykułów, praca 4: 1401 artykułów). W pracy 3 dokonałam analizy dostępnej wiedzy dotyczącej metod kontrolowania pozycji siekaczy, podczas ich retrakcji w toku leczenia kamuflującego wad klasy II. Wykazałam, że dwustronna kortykotomia oraz zastosowanie miniimplantów do retrakcji en masse sa najlepszymi i skutecznymi metodami kontroli torku podczas retrakcji siekaczy w leczeniu ortodontycznym. W pracy 4 zbadałam zakres dostępnej wiedzy w zakresie charakterystyki remodelingu kości wyrostka zębodołowego w czasie retrakcji siekaczy szczęki. Analiza dostępnych publikacji wykazała, że w wyniku retrakcji siekaczy następuje znaczna utrata kości, co zmniejsza odległość między powierzchnią kości a powierzchnią korzenia od strony podniebiennej.

W kolejnej pracy oryginalnej (praca: 5) dokonałam analizy biomechaniki retrakcji zębów szczęki w przypadkach ekstrakcyjnych i nieekstrakcyjnych za pomocą nowatorskiej metody nielinearnej analizy metodą elementów skończonych. W tej pracy określiłam wartość sił retrakcyjnych mogących skutkować przekroczeniem progu naprężeń optymalnych w więzadłach ozębnej. Przedstawiłam analizę naprężeń w ozębnej wykonaną metodą elementów skończonych, na nowatorskim, nielinearnym modelu szczęki, w trakcie retrakcji zębów górnych. W badaniu jako zmienne badane uwzględniono retrakcję en masse segmentu zębów górnych przednich do miniimplantu (TISAD) umieszczonego w okolicy pomiędzy drugim zębem przedtrzonowym a pierwszym trzonowym oraz dystalizację całego łuku również do TISAD przeprowadzoną na łuku 0.017*0.025 SS w zamkach slotu 0.018, z uwzględnieniem różnych wartości sił i wysokości haczyków wpływających na wektor zastosowanej siły. Wykazałam, że optymalnie łuki 0,017*0,025 SS w zamkach MBT 0,018 zapewniają doskonałą kontrolę torku, prowadząc do precyzyjnego osiowego przemieszczenia zębów, przy zastosowaniu optymalnych sił 180-200g/stronę nie ma ryzyka resorpcji wierzchołka korzenia.

Na podstawie dostępnej wiedzy, poprzez przegląd systematyczny 1862 artykułów (praca: 6) określiłam ryzyko resorpcji siekaczy szczęki, w trakcie ich retrakcji, w związku z kontaktem z blaszką zbitą kanału przysiecznego. Określiłam obecny stan wiedzy na temat wpływu morfologii kanału przysiecznego na możliwość występowania resorpcji korzeni siekaczy górnych w trakcie ich retrakcji w toku leczenia kamuflującego wad klasy II. Wykazałam, że kontakt korzeni siekaczy z kanałem przysiecznym zwiększa ryzyko resorpcji tych korzeni.

Na tej podstawie zaplanowałam badanie oryginalne, opublikowane jako praca 7, w której dokonałam analizy badan CBCT 67 pacjentów. Dokonałam klasyfikacji morfologii kanału przysiecznego pacjentów, w zależności od wieku i płci. Na tej podstawie stworzyłam wykaz zaleceń dotyczących unikania ryzyka resorpcji korzeni siekaczy górnych w trakcie ich retrakcji, w związku z kontaktem ze ścianami kanału przysiecznego. Przeprowadzone przeze mnie badania wykazały różną szerokość kanału siecznego w zależności od płci.

8. Cykl publikacji stanowiących podstawę pracy doktorskiej

8.1 Publikacja 1

diagnostics

MDPI

Systematic Review

New Sagittal and Vertical Cephalometric Analysis Methods: A Systematic Review

Jacek Kotula [1,*], Anna Ewa Kuc [2], Joanna Lis [1], Beata Kawala [1] and Michal Sarul [1]

[1] Department of Dentofacial Orthopedics and Orthodontics, Wroclaw Medical University, Krakowska 26, 50-425 Wroclaw, Poland; joanna.lis@umed.wroc.pl (J.L.); beata.kawala@umed.wroc.pl (B.K.); michal.sarul@umed.wroc.pl (M.S.)
[2] Dental Star Specjalistyczne Centrum Stomatologii Estetycznej, 15-215 Białystok, Poland; dental.star@wp.pl
* Correspondence: j_kotula@poczta.onet.pl

Abstract: Cephalometric analysis is an essential tool used in orthodontic diagnosis and treatment planning. The main objectives of correct cephalometric analysis include resolving anteroposterior and vertical maxillary and mandibular base discrepancies. For a diagnostic tool to be of value, it should be precise, reliable and reproducible. Unfortunately, according to some studies, the accuracy of input and, therefore, the diagnostic reliability of some of the points and measurements may not be satisfactory. To this end, new cephalometric measurements are being developed with increased precision. In order to properly and definitively determine the usefulness of a given measurement in cephalometric diagnosis, it is necessary to carry out a critical evaluation of available studies. The aim of this systematic review was to evaluate the available scientific literature describing new landmarks and reference linear and angular measurements of 2D cephalometric analyses assessing the sagittal and vertical discrepancy in the position of jaw bases since the last systematic review in 2013. The secondary aim was to assess the accuracy and reliability of new anthropometric landmarks and reference planes in relation to those used previously, and their instability in relation to growth and orthodontic tooth movements. To carry out the intended plan, electronic databases such as PubMed, Scholar Google, Web of Science and Pro Quest were searched using specific keywords. Initially, a total of 1451 articles were retrieved. Then, duplicate articles in all databases were excluded from the resulting publications. The results showed that despite such a high number of articles published in peer-reviewed scientific journals, only 12 studies on new cephalometric analyses in the sagittal plane and 4 studies on new cephalometric analyses in the horizontal plane met the criteria and, as a result, were included in the review.

Keywords: cephalometric analysis; sagittal discrepancy; vertical discrepancy

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1. Introduction

Methods of conducting the cephalometric analysis of lateral head radiographs in two-dimensional visualisation have been developed since their pioneering use by Broadbent in the USA and Hofrath in Germany that took place in 1931 [1–8]. Since then, cephalometric analysis has been one of the basic instruments used routinely in the diagnosis and planning of orthodontic treatment [3]. Although only a small percentage of orthodontic treatment plans are modified [9] on the basis of cephalometric analysis [1], its results allow the orthodontist to plan a comprehensive therapeutic process that is improved [2]. A correct cephalometric analysis is particularly important in borderline cases when an extraction or orthognathic/surgical treatment plan is considered [4].

Admittedly, modern orthodontics is increasingly using CBCT imaging. However, given the number of scientific studies on 2D cephalometric analyses and the need for the radiological protection of the patient, 2D lateral cephalograms remain the primary diagnostic examination in orthodontic assessment and treatment planning.

To date, many new analyses have been developed, each containing some new measurements and/or reference values [2]. Despite the numerous papers published in peer-reviewed scientific journals in this field [1], the actual value of this imaging technique in orthodontic treatment planning has not been scientifically proven. This is mainly due to the instability of the reference points used in cephalometric diagnosis in relation to changes in growth type and the therapeutic process used. Due to the inaccuracy and differences in the interpretation of the positions of numerous landmarks in 2D lateral cephalograms, new landmarks are being sought that will not change location during the growth process or as a result of tooth movement during treatment. Examples of such measurements include:

1. YEN angle formed by the points S, M, G defining the sagittal relationship between the maxilla and the mandible, first described by Neel et al. in 2009 [10].
2. Pi analysis referring to the angular measurement Pi (GG'M) and the linear measurement Pi (G'M') based on the points G, M from which the perpendicular goes to the true horizontal plane in the natural position of the head, defining the sagittal relationship between the maxilla and the mandible [11], first described by Kumar et al. in 2012 [12]
3. W angle formed by the points S, M, G, defining the sagittal relationship between the maxilla and mandible, first described by Bhad et al. in 2011 [13]
4. SAR angle formed by the points M, G, W, defining the sagittal jaw base discrepancy, described by Sonahita et al. in 2015 [14]
5. DW angle using Walker and Wing (WW) points to assess the sagittal discrepancy, described by Hatewar et al. in 2015 [15]
6. Tau angle formed by the points T, M, G, defining the sagittal relationship between the maxilla and the mandible, first described by Gupta et al. in 2020 [6]
7. R angle formed by the points N, C, Me to assess the vertical discrepancy, first described by Rizwan and Mascarenhas in 2013 [16]
8. KP (extraoral) plane and points NS, SAE bilaterally to assess the vertical discrepancy, first described by Kattan et al. in 2018 [17]
9. Superior border of the zygomatic arch to assess the vertical discrepancy as an alternative to the Frankfurt horizontal line introduced by Park et al. in 2019 [18]

However, to confirm the diagnostic effectiveness of the above-mentioned measurements, it is necessary to carry out a thorough analysis and comparison of studies on their use. The aim of this study was to evaluate the available scientific literature describing new landmarks and reference linear and angular measurements of 2D cephalometric analyses assessing the sagittal and vertical discrepancies in the positions of jaw bases.

2. Methods Protocol and Registration

The protocol for this review was registered on the International Prospective Register of Systematic Reviews (PROSPERO) database (CRD...) available from https://www.crd.york.ac.uk/prospero ... (accessed on 1 February 2022). The present systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [19] and the Cochrane Handbook for Systematic Reviews of Interventions [20]. The PRISMA flow diagrams summarize all steps in the selection of included studies, were built using an online tool [21] and included eligibility criteria and study participant characteristics. The eligibility criteria for the included studies were defined considering the PICO strategy. The types of studies included in the systematic review were randomized controlled trials, nonrandomized clinical trials, and observational studies. Case reports, case series, letters, comments, short communications, pilot studies (ten patients or fewer), animal studies, in vitro studies, in silico studies, and literature reviews were excluded. The eligible studies were full-text articles in English and Russian with publication date during 2009 to 2021.

3. Information Sources and Search Strategy

The search was performed in the electronic databases PubMed and Web of Science; Scholar Google and Pro Quest were used for the identification of the registers and protocols for the clinical trials. The manual search was achieved through examining the bibliographical references of the studies included in the review. This search was carried out from September 2021 to December 2021. The keywords and algorithms used for the search strategy are shown in Table 1. Two reviewers (JK and PS) performed the search and selection. In the absence of unanimity between the researchers, MS had the final say.

Table 1. The algorithms used in the search strategy updated for each database and question.

Pico strategy	Population: Patients with orthodontic treatment Interventions: cephalometric 2D Comparator: Q1 = sagittal analyses, Q2 = horizontal analyses Outcomes: new indicator of sagittal dysplasia: YEN angle, W angle, Pi angle, Tau angle, SAR angle, ODI, APDI, HBN angle, DW plane, AF–BF, Another analysis ANB Angle, Wits marker, ROC, beta angle, Downs angle, AB plane angle
Focused questions	Q1 = Wich is the effect on the new landmarks and measurements in the cephalometric analyses vs. conventional analyses of the sagittal relationships of the jaws Q2 = Wich is the effect on the new landmarks and measurements in the cephalometric analyses vs. conventional analyses of the horizontal relationships of the jaws
Number of registers found for each database	Algorithms used in the search strategy adapted for each database and question
PubMed Q1 = 1451 (12) Q2 = 1451 (8)	Q1 = Cephalometr* and (orthodontic* or 'orthodontic treatment planning') and ('efficacy' or 'reproducibility' or 'repeatability' or 'reliability' or 'accuracy' or 'validity' or 'validation' or 'precision' or 'variability' or 'efficiency' or 'comparison') and (YEN Angle or W Angle or Pi Angle or Tau Angle or SAR Angle or ANB Angle or Wits marker or ODI or APDI or ROC or Beta Angle or Downs Angle or AB plane Angle or HBN Angle or DW plane or AF-BF) not ('Cone-Beam Computed Tomography' or 'Three-Dimensional imaging' or 'Cone Beam Computed Tomography' or 'Cone Beam CT' or 'Volumetric Computed Tomography' or 'Volume Computed Tomography' or 'Volume CT' or 'Volumetric CT' or 'Cone beam CT' or 'CBCT' or 'digital volume tomography' or 'DVT' or 'Spiral Computed Tomography' or 'Spiral Computer-Assisted Tomography' or 'Spiral Computerized Tomography' or 'spiral CT Scan' or 'spiral CT Scans' or 'Helical CT' or 'Helical CTS' or 'Helical Computed Tomography' or 'Spiral CAT Scan' or 'Spiral CAT Scans' or '3D' or '3-D' or 'three dimension*').) AND (("2015/01/01"[Date—Completion]: "3000"[Date—Completion])) Q2 = Cephalometr* and (orthodontic* or 'orthodontic treatment planning') and ('efficacy' or 'reproducibility' or 'repeatability' or 'reliability' or 'accuracy' or 'validity' or 'validation' or 'precision' or 'variability' or 'efficiency' or 'comparison') and (ODI or DW plane or zygomatic arch or foramina of the trigeminal nerve landmarks or Frankfurt line or orbito-ingotic line or gonial angle or AF-BF) not ('Cone-Beam Computed Tomography' or 'Three-Dimensional imaging' or 'Cone Beam Computed Tomography' or 'Cone Beam CT' or 'Volumetric Computed Tomography' or 'Volume Computed Tomography' or 'Volume CT' or 'Volumetric CT' or 'Cone beam CT' or 'CBCT' or 'digital volume tomography' or 'DVT' or 'Spiral Computed Tomography' or 'Spiral Computer-Assisted Tomography' or 'Spiral Computerized Tomography' or 'spiral CT Scan' or 'spiral CT Scans' or 'Helical CT' or 'Helical CTS' or 'Helical Computed Tomography' or 'Spiral CAT Scan' or 'Spiral CAT Scans' or '3D' or '3-D' or 'three dimension*').) AND (("2015/01/01"[Date—Completion]: "3000"[Date—Completion]))

Table 1. Cont.

Google Scholar Q1 = 7 (1) Q2 = 0	Q1 = Cephalometr * and (orthodontic * or 'orthodontic treatment planning') and ('efficacy' or 'reproducibility' or 'repeatability' or 'reliability' or 'accuracy' or 'validity' or 'validation' or 'precision' or 'variability' or 'efficiency' or 'comparison') and (YEN Angle or W Angle or Pi Angle or Tau Angle or SAR Angle or ANB Angle or Wits marker or ODI or APDI or ROC or Beta Angle or Downs Angle or AB plane Angle or HBN Angle or DW plane or AF-BF) not ('Cone-Beam Computed Tomography' or 'Three-Dimensional imaging' or 'Cone Beam Computed Tomography' or 'Cone Beam CT' or 'Volumetric Computed Tomography' or 'Volume Computed Tomography' or 'Volume CT' or 'Volumetric CT' or 'Cone beam CT' or 'CBCT' or 'digital volume tomography' or 'DVT' or 'Spiral Computed Tomography' or 'Spiral Computer-Assisted Tomography' or 'Spiral Computerized Tomography' or 'spiral CT Scan' or 'spiral CT Scans' or 'Helical CT' or 'Helical CTS' or 'Helical Computed Tomography' or 'Spiral CAT Scan' or 'Spiral CAT Scans' or '3D' or '3-D' or 'three dimension*').) AND (("2013/01/01"[Date—Completion]: "3000"[Date—Completion])) Q2 = Cephalometr* and (orthodontic* or 'orthodontic treatment planning') and ('efficacy' or 'reproducibility' or 'repeatability' or 'reliability' or 'accuracy' or 'validity' or 'validation' or 'precision' or 'variability' or 'efficiency' or 'comparison') and (ODI or DW plane or zygomatic arch or foramina of the trigeminal nerve landamrks or francfort line or orbito-ingotic line or gonial angle or AF-BF) not ('Cone-Beam Computed Tomography' or 'Three-Dimensional imaging' or 'Cone Beam Computed Tomography' or 'Cone Beam CT' or 'Volumetric Computed Tomography' or 'Volume Computed Tomography' or 'Volume CT' or 'Volumetric CT' or 'Cone beam CT' or 'CBCT' or 'digital volume tomography' or 'DVT' or 'Spiral Computed Tomography' or 'Spiral Computer-Assisted Tomography' or 'Spiral Computerized Tomography' or 'spiral CT Scan' or 'spiral CT Scans' or 'Helical CT' or 'Helical CTS' or 'Helical Computed Tomography' or 'Spiral CAT Scan' or 'Spiral CAT Scans' or '3D' or '3-D' or 'three dimension*').) AND (("2013/01/01"[Date—Completion]: "3000"[Date—Completion]))
Pro Quest Q1 = 112 (2)	Cephalometr* and (orthodontic* or 'orthodontic analysis') and (2D lateral cephalometry) and (W angle or YEN angle or Pi ANgle or Tau Angle)
Web of Science Q1 = 1 Q2 = 0	Q1 = Cephalometr and (orthodontic or 'orthodontic analysis) Q2 = Cephalometr and (orthodontic or 'orthodontic analysis)

4. Materials and Methods

To prepare the systematic review, the electronic databases PubMed, Google Scholar, Pro Quest, and Web of Science were searched to find publications that met the inclusion criteria. No attempt was made to explore informally published articles, conference materials or abstracts of presentations given at scientific conferences. The search was conducted from 2013, the end of the previous systematic review, to 2021, extended backward to 2009 to include analyses published between 2009 and 2013 that were not included in the previous publication.

5. Selection of Material

Articles were included in this publication in two stages. In the first stage, two orthodontist reviewers (JK and PS) independently reviewed PubMed, Scholar Google Pro Quest, and Web of Sciences using keywords corresponding to the criteria specified in the paper (Table 1). Studies eligible for inclusion in the systematic review were determined by the title and abstract of each record identified by the search.

Then, in the retrieved database of articles, two reviewers made an initial selection of articles that met the search criteria in accordance with the research topic. The following were used as exclusion criteria:

- Publications in languages other than English and Russian;
- Publications published before 2009;
- Publications that appeared repeatedly in various databases;
- Publications whose full texts were not made available online;
- Publications evaluating soft tissue analysis.

After initial screening, abstracts of the retrieved publications were analysed and categorised by research topic by each of the two reviewers. At this stage, publications were excluded according to the following criteria:

- Article objectives were irrelevant to the subject of this review;
- Articles covered the topic of cone–beam computed tomography;
- Articles were related to three-dimensional analysis.

Each article included in the next selection stage had to be favourably evaluated by at least one of the reviewers; in the absence of unanimity, the third reviewer had the casting vote. At this stage, full texts of articles were downloaded and subjected to critical analysis. Bibliographies and reference lists of publications that were considered relevant in the first stage were searched manually. The aim of this review was to evaluate parent studies. A detailed selection tree is shown in Figure 1a,b [11].

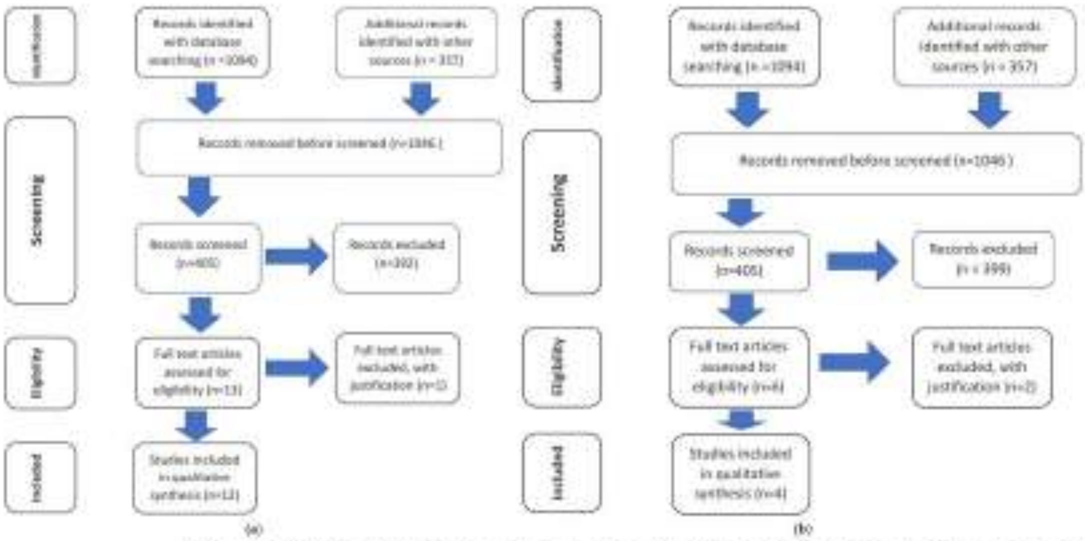

Figure 1. (a) The methodology used to select articles in relation to sagittal analysis. (b) The methodology used to select articles in relation to horizontal analysis [5].

The collected articles were subjected to risk of bias analysis according to Liu et al. [22] (Table 2a relative to Q1 and Table 2b relative to Q2).

The quality and internal relevance (level of reliability) of each publication were rated as high, moderate or low according to the criteria indicated in a review by Durão et al. [1].

Table 2. (**a**) The risk-of-bias analysis of articles evaluating new cephalometric analysis parameters in relation to the sagittal plane. (**b**) The risk-of-bias analysis of articles evaluating new cephalometric analysis parameters in relation to horizontal plane.

(a)

	Author (year)	Neela 2009 [10]	Bhad 2011 [13]	Kumar 2012 [12]	Kumar 2014 [20]	Sonahita, A.; 2014 [14]	Hatewar 2015 [15]	Ali, S.M.; 2018 [16]	Ahmed 2018 [25]	Shetty 2014 [26]	Gupta 2020 [4]	Jedliński 2020 [7]	Gokhan 2021 [9]
Q1	A confounding	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
	B selection bias	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
	C classification of interventions	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
	D deviations from intervention	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
	E missing data	Green	Green	Green	Green	Green	Green	Yellow	Green	Green	Green	Green	Green
	F measuring the results	Green	Green	Green	Yellow	Green	Green	Green	Green	Yellow	Green	Yellow	Green
	G reporting bias	Green	Green	Green	Yellow	Green	Green	Green	Green	Yellow	Green	Yellow	Green
	H overall	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow

(b)

	Author (year)	Rizwan 2013 [18]	Ahmed M. 2016 [23]	Kattan EE. 2018 [17]	Park JA. 2019 [18]
Q2	A confounding	Yellow	Yellow	Yellow	Yellow
	B selection bias	Green	Green	Green	Green
	C classification of interventions	Green	Green	Green	Green
	D deviations from intervention	Green	Green	Green	Green
	E missing data	Green	Green	Green	Green
	F measuring the results	Green	Green	Green	Green
	G reporting bias	Green	Green	Green	Yellow
	H overall	Yellow	Yellow	Yellow	Yellow

○ Yellow unclear risk. ○ Green—low risk.

5.1. *Levels of Evidence and Criteria for Synthesising Evidence*

5.1.1. High Level of Evidence

Research was classified as having a high level of evidence if it met all of the following criteria:

- An independent blind comparison between test and reference methods was performed (in Table 3a relative to Q1 and Table 3b relative to Q2, marked as A).
- Population was described in such a way that the condition, prevalence and severity of the condition were clear. The spectrum of patients was similar to the spectrum of patients on whom the research method would be used in clinical practice (in Table 3a relative to Q1 and Table 3b relative to Q2, marked as B).
- The test method results did not influence the decision to perform reference method (in Table 3a relative to Q1 and Table 3b relative to Q2, marked as C).
- The test and reference methods are well described in terms of technique and implementation (in Table 3a relative to Q1 and Table 3b relative to Q2, marked as D).
- The evaluations (observations and measurements) were well described, giving the diagnostic criteria used as well as information and instructions to observers (in Table 3a relative to Q1 and Table 3b relative to Q2, marked as E).
- The reproducibility of the research method was described for one observer (intra-observer action) and for several (minimum 3) observers (inter-observer action) (in Table 3a relative to Q1 and Table 3b relative to Q2, marked as F).
- The results are presented as relevant data needed for necessary calculations (in Table 3a relative to Q1 and Table 3b relative to Q2, marked as G).

Table 3. (a) The evaluation of the conclusions according to the degree of evidence of articles discussing new indicators of cephalometric analysis in relation to the sagittal plane. (b) The evaluation of the conclusions by degree of evidence of articles discussing new indicators of cephalometric analysis in relation to the horizontal plane.

(a)

	Author (year)	Neela 2009 [10]	Bhad 2011 [11]	Kumar 2012 [12]	Kumar 2014 [23]	Sonahita 2014 [14]	Hatewar 2015 [15]	Ali 2018 [24]	Ahmed 2018 [25]	Shetty 2019 [26]	Gupta 2020 [6]	Jedliński 2020 [7]	Gokhan 2021 [8]
Q1	Level of evidence	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Green	Yellow	Green	Yellow	Green	Yellow

(b)

	Author (year)	Rizwan 2015 [16]	Ahmed M. 2016 [27]	Kattan EE. 2008 [17]	Park JA. 2019 [28]
Q2	Level of evidence	Yellow	Yellow	Green	Green

Yellow—moderate level of evidence, Green—low level of evidence.

5.1.2. Moderate Level of Evidence

Research was assessed as having a moderate level of evidence if any of the above criteria were not met. On the other hand, a study with any of the deficits described below was assessed as having a low level of evidence.

5.1.3. Low Level of Evidence

Research was judged to have a low level of evidence if it met any of the following criteria:

- The evaluation of the test and reference methods was independent (A).
- The population was not clearly described, and the spectrum of patients was distorted (B).
- The test method results influenced the decision to perform reference method (C).
- The test, reference method or both were not well described (D).
- The results were not well described (E).
- The reproducibility of the research method was not described or was only described for one observer (F).
- The results may have a systematic bias (H).

- The results were not presented in a way that enabled calculating effectiveness (G).

Quality assessments of the included research were performed using the risk-of-bias table in RevMan 5.3 for RCTs (Table 2a,b).

5.2. Evidence-Based Evaluation of Conclusions

The scientific evidence for the conclusions on diagnostic efficacy was considered strong, moderately strong, limited or insufficient depending on the quality and internal relevance (level of credibility) of the publications evaluated.

- Strong research-based evidence: at least two publications or a systematic review must have a high level of evidence.
- Moderately strong research-based evidence: One publication must have a high level of evidence, and two subsequent publications must have a moderate level of evidence.
- Limited research-based evidence: at least two publications must have a moderate level of evidence.
- Insufficient research-based evidence: scientific evidence is insufficient or non-existent according to the criteria defined in this research.

Articles presented in the PRISMA flow diagram that obtained a minimum of 4 points were selected for final analysis (Table 2).

The results presented in the selected articles are summarised in Table 4a,b.

5.3. Evidence Synthesis

The results of this review are presented descriptively.

Table 4. (a) Publication analysis of parameters in sagittal discrepancy analysis. (b) Publication analysis of parameters in vertical discrepancy analysis.

(a)

	Authors (Year)	Title	Aim of the Study	Observers	Stadium Project	Statistical Method	Results According to Authors	Level of Evidence
2009	Neela PK, Mascarenhas R, Husain A. [10]	A new sagittal dysplasia indicator: the YEN angle.	The development of a new cephalometric measurement to assess the sagittal relationship between maxilla and mandible. YEN angle.	75 lateral cephalograms before treatment (25 each in classes I, II and III)	The new measurement is based on landmarks S, M (midpoint of the anterior maxilla) and G (centre mandibular symphysis). YEN angle measured in M.	The mean and standard deviation for YEN angle were calculated in all three skeletal groups. One-way analysis of variance (ANOVA) and Newman–Keuls test were used.	Aim: to improve the reliable assessment of sagittal relationship between the two jaws. 117° < YEN < 123° skeletal class I. With YEN < 117° skeleton class II. YEN > 123° skeletal class III.	moderate
2011	Bhad WA, Nayak S, Doshi UH. [11]	A new approach to the assessment of sagittal dysplasia: the W angle.	The development of a new cephalometric measurement to assess the sagittal relationship between maxilla and mandible. W angle.	142 cephalometric radiographs before treatment of patients aged 15 to 25 years.	The new measurement is based on landmarks S, M (midpoint of the anterior maxilla) and G (centre mandibular symphysis) and W angle measured between the perpendicular from point M on the S-G line and on the M-G line.	Mean and standard deviation for W angle were calculated. One-way analysis of variance and Newman–Keuls test were applied.	51° < W < 56° skeletal class I. W < 51° degrees skeletal class II. W > 56° degrees skeleton class III.	moderate

Table 4. Cont.

(a)

	Authors (Year)	Title	Aim of the Study	Observers	Stadium Project	Statistical Method	Results According to Authors	Level of Evidence
2012	Kumar S, Valiathan A, Gautam P, Chakravarthy K, Jayaswal P. [12]	An evaluation of the Pi analysis in the assessment of the anteroposterior jaw relationship.	The development of a new cephalometric measurement to assess the sagittal relationship between maxilla and mandible. Pi angle and the linear value of Pi.	355 persons average age 19.7 years.	The trial was divided into class I, II or III skeletal groups based on the ANB angle. Descriptive data were calculated for each variable and group.	The correlation coefficients between class I parameters were calculated. Coefficient of determination, regression coefficient, regression equation, standard error of estimation.	x̄ 3.40 (±2.84) class I x̄ 8.94 (±5.30) class II x̄ −4.57 (±1.61) class III For linear Pi = 3.40 (±2.30) class I, Pi = 8.90 (±3.56) class II Pi = −3.30 (±2.30) class III Pi angle > 5°: 88% sensitivity, 92% specificity in distinguishing class II skeletal group from class I. Pi angle < 1.3°: 100% sensitivity, 84% specificity in distinguishing class III skeletal groups from class I. The accuracy of distinguishing class II groups from class I was > 90% and that of class III from class I > 90%. The cut-off point between classes I and II may be regarded as the angle Pi = 5° between classes I and III, Pi = 1.3°. No correlation Pi-ANB Pi-Beta, Pi-WITS. The highest level of correlation was obtained for angle Pi and linear Pi (0.86).	moderate

Table 4. Cont.

	Authors (Year)	Title	Aim of the Study	Observers	[illegible] Project	Statistical Method	Results According to Authors	Level of Evidence
2014	Kumar V., Sundareswaran S., [133]	Cephalometric Assessment of Sagittal Dysplasia: A Review of Twenty-One Methods	The review provides an insight into the various cephalometric methods used to assess the sagittal relationships of jaws in chronological order and their implications in modern orthodontics.	21 analyses of the sagittal plane	Fixed values for linear measurements were discussed Clinoid lower-sella Sella–Ptm Maxillary length Ptm-to-upper 6 Mandibular length of angle measurements: angle between N-Pog and AB line Angle of convexity NA to APog ANB angle Taylor's AB' distance To orthogonal projection on SN of the line and orthogonal to this line drawn from A AXD angle and AD distance Wits APDI angle AXB angle JYD angle Maxillo-mandibular difference calculated as the angle between A–Co and Gn–Co AF–BF distance (distance between projections A and B on the Frankfurt plane Quadrilateral analysis between SN–PP–G–TG and NAG angle APP–BPP distance as a distance between projections A and B on PP (plane of the jaw base ANS–PNS TABA analyses of the angles of AB to TH and AB to the parallel of TH through A Beta angle formed by Co–B, AB plane and the orthogonal to Co–B descending from A Yen-SMG angle	none	Details of 21 measurements to determine maxilla and mandible sagittal position	low

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Table 4. Cont.

	Authors (Year)	Title	Aim of the Study	Observers	[illegible] Project	Statistical Method	Results According to Authors	Level of Evidence
2015	Sunahia A.; Jitendra R.; Praveen M.; Sudhir K.; Kumar [R] [134]	The SAR Angle: A Contemporary Sagittal Jaw Dysplasia Marker.	The aim is to determine means and standard deviation for this angle in persons with skeletal classes I, II and III.	60 pretreatment lateral cephalograms of 13–25 years old patients	SAR angle is a new parameter for assessing apical base sagittal discrepancy. It uses three skeletal reference points: Point M: Midpoint of the premaxilla Point G: Centre of the largest circle that is tangent to the internal inferior, anterior and posterior surfaces of the mandibular symphysis Point W (Walker's point): The mean intersection point of the lower contours of the anterior clinoid processes (ACP) and the contour of the anterior wall of the sella turcica. The three lines that would form joining these points include • the line connecting Point M and Point G • the line connecting Point W and Point G • and the line from point M perpendicular to the W–G line. The angle to measure is between the perpendicular line from point M to W–G, while the M–G line is the SAR angle	The data were summarized as mean ± SD. Groups were compared by factor analysis (gender and class), analysis of variance and Newman–Keuls post hoc test. Receiver operating characteristics (ROC) curve analysis was performed to evaluate the sensitivity and specificity of SAR angle as a differential test between the three skeletal groups.	The mean SAR angle = [illegible]° (SD 2.24), Class I skeletal pattern group SAR angle = 58.18° (SD 2.78) Class II SAR angle = 65.65° (SD 2.25) Class III skeletal group 55° < SAR < 59°: Class I skeletal pattern; SAR < 55°: Class II skeletal pattern SAR > 59°: Class III skeletal pattern.	moderate

Table 4. Cont.

(a)								
	Authors (Year)	Title	Aim of the Study	Observers	Study Project	Statistical Method	Results According to Authors	Level of Evidence
2013	Hatewar SK, Reddy CD, Singh JR, Jain M, Munje S, Khandelwal P [17]	A new dimension to cephalometry: DW plane. The access to the skeletal jaw discrepancy using Walker's point.	This study aims to establish a new cephalometric measurement to assess skeletal jaw discrepancy using Walker's point.	100 lateral cephalograms of indigenous peoples of the Americas aged 8–10, 12–18, 19–27 years.	Point A, Point B, Walker's point (W) and wing point (w) were used for indicating the severity and type of skeletal dysplasia. Double W (DW) was constructed joining the Walker's and wing points.	The analysis of variance and Student's t-test were applied, which revealed significant results.	The DW plane is an effective way to accurately establish skeletal jaw relationships. It analyses the distance between linear measurements to determine the sagittal jaw relationship, linear measurements for vertical maxillary height and angular measurements to determine rotational jaw changes. This linear difference of 8.2 ± 0.8 mm indicated a Class I skeletal pattern.	low

Table 4. Cont.

(a)								
	Authors (Year)	Title	Aim of the Study	Observers	Study Project	Statistical Method	Results According to Authors	Level of Evidence
2018	Ali SM, Manjunath G, Sharief A [24]	A Comparison of 3 New Cephalometric Angles with ANB and Wits Appraisal for Assessing Sagittal Jaw Relationship	To study the comparison of ANB and Wits appraisal with 3 new cephalometric angles.	100 lateral cephalometric radiographs	ANB angle evaluation, Wits evaluation, beta angle, AB plane angle, YEN angle and W angle.	Student's t-test	Student's t-test showed, in Class I = 100% correlation with ANB. The closest angle was W angle when compared with ANB and Wits appraisal. In the Class II samples, beta angle was closest compared with ANB, whereas Yen and W angles showed considerable differences in comparison with ANB and Wits appraisal. The comparisons of beta, Yen, and W angles with ANB angle and Wits appraisal in Class III samples revealed no significant differences. The statistical comparison of the overall mean beta, yen, and W angles was 0.50, 0.47, and 0.53, respectively, for Classes I, II, and III samples with ANB and Wits = 100% correlation compared with ANB and Wits appraisal. There is no gold standard for ANB angle. Beta, Yen, and W angles are not accurately consistent, showing varying results for classes I–III compared with ANB.	moderate

Table 4. Cont.

	(a)							
	Authors (Year)	Title	Aim of the Study	Observers	Studium Project	Statistical Method	Results According to Authors	Level of Evidence
2018	Ahmed M., Shaikh A., Fida M. [25]	Diagnostic validity of different cephalometric analyses for assessment of the sagittal skeletal pattern.	Reliability and reference assessment of various skeletal analyses to identify sagittal skeletal pattern.	148 persons (men = 79, women = 69, mean age = 23.6 ± 4.6 years).	The assessment of the anteroposterior skeletal system using: ANB angle, Wits, Beta angle, angle of the AB plane, Downs convexity angle, W angle.	The accuracy and reliability of the above analyses were determined using the Kappa statistic, sensitivity and positive predictive value (PPV).	ANB highest diagnostic agreement (k = 0.802). In the class I group, Downs convex angle showed the highest sensitivity (0.968), and ANB showed the highest PPV (0.930). In the class II group, ANB angle (0.928) and PPV (0.951) showed the highest sensitivity. In the class III group, ANB angle, Wits appraisal and Beta angle showed sensitivity (0.902). Downs convex angle and ANB angle showed the highest sensitivity (1.00). Conclusion: the ANB angle was found to be the most relevant and reliable indicator in all sagittal groups. Downs angle, Wits appraisal and Beta angle can be used as valid indicators to assess class III sagittal pattern.	moderate

Table 4. Cont.

	(a)							
	Authors (Year)	Title	Aim of the Study	Observers	Studium Project	Statistical Method	Results According to Authors	Level of Evidence
2019	Shetty SK., Desai G., Kumar M., Madhur VK., Alphonse TM., [26]	Cephalometric Assessment of Anteroposterior Discrepancy: A Review of Various Analyses in Chronological Order	Previously established parameters like: ANB angle, Wits, AF-BF, APDI, Beta angle, Yen angle, W angle, Pi analysis, SAR angle, FBN angle, DW plane. Chronologic order and its clinical implications in contemporary orthodontics.	21 analyses	Previously, a total of 21 cephalometric analyses were performed to determine the anteroposterior position of the mandible in the sagittal plane.	none	The rotational effects of jaws, variable positions of points A and B, nasion, variations in cranial base length, tooth eruption, curve of Spee, etc., appear to influence anteroposterior assessment, resulting in the employment of extracranial reference planes as well. One cephalometric analysis may not result in an accurate diagnosis. Moreover, cephalometry is not a specific science or method, and therefore numerous analyses supported by angular and linear parameters have obvious limitations.	low

Table 4. Cont.

				(a)				
	Authors (Year)	Title	Aim of the Study	Observers	Studium Project	Statistical Method	Results According to Authors	Level of Evidence
2022	Gupta P, Singh N, Tripathi T, Gopal R, Rai P. [16]	Tau Angle: new approach to assessing true sagittal skeletal maxillo-mandibular relationship.	Present new Tau angle used in cephalometric analysis.	Age group of 13- to 30-year-olds. Class I consisted of 101 patients (51 males, 50 females). Class II consisted of 101 patients (51 males, 50 females). Class III consisted of 77 patients (37 males, 40 females).	Tau angle is a novel parameter for determining the true bony sagittal maxillomandibular relationship. Tau angle is constructed by marking three cephalometric landmarks: Point T: The uppermost point at the junction of the frontal wall of the pituitary fossa and tuberculum sellae; Point M: The constructed point representing the centre of the biggest circle that is tangent to the frontal, upper and palatal surfaces of the maxilla; Point G: The focal point of the biggest circle that is tangent to the inner frontal, posterior and lower edges of the mandibular symphysis. Tau angle lies between the two lines connecting T and G points as well as M and G points. This study aims to establish Tau angle's mean and standard deviation for three skeletal malocclusions.	The normality of the data was assessed by skewness, kurtosis and Shapiro–Wilk test. ANOVA and Dunnett's T3 post hoc test determine differences among the three skeletal patterns. Student's t-test	The mean and standard deviation for Tau angles in the class I, II, and III groups were 31.93 (±1.68)°, 36.32 (±2.90)° and 25.54 (±2.80)°, respectively. The ANOVA and Dunnett's T3 test revealed significant differences in the mean Tau angle among three groups ($p < 0.05$). T-tests conveyed no significant difference in terms of Tau angle values between sexes in each skeletal pattern. Tau angle at 34.25° is 96% sensitive and 98% specific in differentiating class II and I. Therefore, ROC curves set the Tau angle cut-off points of class III and II skeletal patterns with class I to be approximately 28.5° and 34.25°, respectively.	moderate

Table 4. Cont.

				(a)				
	Authors (Year)	Title	Aim of the Study	Observers	Studium Project	Statistical Method	Results According to Authors	Level of Evidence
2022	Jodkowski M., Janiszewska-Olszowska J., Grocholewicz K. [17]	Description of the sagittal jaw relation in cephalometric analysis—a review of literature	present the most frequently used cephalometric measurements to assess the skeletal class on a lateral cephalometric headfilm		ANB angle, WITS appraisal, APDI, Harvold analysis	none	ANB angle cannot be used as the only indicator of sagittal skeletal discrepancy. WITS appraisal is independent of the variability of cranial base structures and thus may be an important supplement to the diagnosis, although it depends on the variability of the occlusal plane. APDI can reliably distinguish between class I, II and III malocclusion.	low

Table 4. Cont.

			(a)				
	Authors (Year)	Title	Aim of the Study	Objectives	Study Project	Statistical Method	Results According to Authors	Level of Evidence
2021	Tarkey G., Ozturk T., Coban G., Yagci? [illegible]	Evaluation of Various Sagittal Cephalometric Measurements in Skeletal Class I Individuals with Different Vertical Facial Growth Types	This study aims to compare various cephalometric measurements and show the relationships between beta, W and Yen angles and the sagittal dimension of the maxilla and mandible in individuals with different vertical facial growth types		150 lateral cephalograms with different types of vertical facial growth with low-angle (LA), norm-angle (NA), high-angle (HA) and Class I malocclusion. The following were assessed and compared with each other: ANB angle, Wits appraisal, A-Nperp, Pog-Nperp, Beta angle, W angle, Yen angle	The Kolmogorov–Smirnov and Shapiro–Wilk tests, Levene's test, analysis of variance, Kruskal–Wallis test, Mann–Whitney U test, Spearman correlation test. Statistical significance value was set as $p = 0.05$.	Analysis parameters of Wits appraisal, Pog-Nperp, Beta, W and Yen angles were significantly different among groups ($p < 0.05$). The Wits analysis, Pog-Nperp and Yen angles were found to be significantly lower in HA participants compared with LA participants, while the beta angle was found to be significantly higher in HA participants compared with LA participants ($p < 0.05$). Beta and W angles were significantly lower in NA patients than in HA patients ($p < 0.05$). ANB, beta, W and Yen angles show significant correlations regardless of vertical face growth type ($p < 0.05$)	moderate

Table 4. Cont.

				(b)				
Q2	Authors (Year)	Title	Aim of the Study	Objectives	Number of Participants	Study Project	Statistical Method	Results According to Authors	Level of Evidence
	2013	Rizwan M., Mascarenhas R., [illegible]	A new parameter for assessing vertical skeletal discrepancies: the R angle	The study aims to evaluate the reliability of R angle (nasion–centre of the condyle–menton) in assessing the vertical skeletal discrepancies.	60 patients aged 18–26 years.	Evaluation of R angle in low-angle, average-angle and high-angle patient groups. Next, the R angle was individually constructed, measured and compared for each of the three skeletal patterns (high, average and low angle).	The means and standard deviations of R angle for all the three skeletal patterns were obtained using one-way ANOVA. The R angle values as examined by the Newman–Keuls post hoc test revealed that the three skeletal patterns under analysis are different.	Results: R angle < 70.50 indicates low-angle cases, between 70.5–75.50 indicates average-angle cases and > 75.50 indicates high-angle cases. R angle is clinically and statistically significant in assessing vertical skeletal discrepancies. Receiver operating characteristic (ROC) curves indicated that R angle > 70.50 had 81.6% sensitivity and 70% specificity in discriminating the low-angle cases from average-angle cases and R angle > 75.50 had 90% sensitivity and 77.8% specificity in discriminating the average-angle cases from high-angle cases. Therefore, values < 70.50 indicate low-angle cases, between 70.5–75.50 indicate average-angle cases and > 75.50 indicate high-angle cases.	moderate

Table 4. Cont.

Q2	Authors (Year)	Title	Aim of the Study	Observers	Number of Participants	Studium Project	Statistical Method	Results According to Authors	Level of Evidence
	2016	Ahmed M., Shaikh A., Fida M. [23]	Diagnostic performance of various cephalometric parameters for the assessment of vertical growth pattern.	The Y-axis, sella-nasion angle to the mandibular plane (SN-MP), maxillary plane angle to the mandibular plane (MMA), sella-nasion to gonion-gnathion angle (SN-GoGn), Frankfort–mandibular plane angle (FMA), lower anterior facial height and total anterior facial height ratio (LAFH:TAFH) were used for assessing the vertical growth of the craniofacial region.	161 lateral cephalograms (71 men and 90 women) aged 20.6 ± 4.6 years. The participants were divided into 3 groups: hyperdivergent, normodivergent and hypodivergent.	Comparisons: The sella-nasion angle to the mandibular plane (SN-MP), maxillary plane angle to the mandibular plane (MMA), sella-nasion to gonion-gnathion angle (SN-GoGn), Frankfort–mandibular plane angle (FMA), lower anterior facial height and total anterior facial height ratio (LAFH:TAFH).	Kappa statistics were used for comparing the diagnostic accuracy of different analyses. To further validate the results, sensitivity and positive predictive values (PPV) were calculated for each parameter.	SN-GoGn revealed significant intra-class agreement (k = 0.830). In the hypodivergent group, the highest sensitivity was shown by MMA (0.954) and the highest PPV (0.964) by FMA. In the normodivergent group, FMA showed the highest sensitivity (0.909) and the highest PPV (0.982) by SN-GoGn. SN-GoGn showed the highest sensitivity (0.980) and PPV (0.971) in the hyperdivergent group. SN-GoGn and FMA proved to be the most reliable indicators. LAFH and TAFH are the least reliable indicators for assessing the vertical growth pattern.	Moderate

Table 4. Cont.

Q2	Authors (Year)	Title	Aim of the Study	Observers	Number of Participants	Studium Project	Statistical Method	Results According to Authors	Level of Evidence
	2018	Kattan EE., Kattan EM., Elhiny OA. [17]	A new horizontal plane of the head.	This study attempts to introduce a new extracranial horizontal plane of the head (plane K that extends from SN to SAE bilaterally) that could act as a substitute for the Frankfort horizontal intracranial reference plane both clinically and radiographically.	A prospective study of 40 participants including 20 men and 20 women.	The establishment of a stable anthropometric plane K compared with the Frankfort plane when stabilized with the extraoral criterion for the determination of NHP.	Descriptive statistics were used: mean, standard deviation and Student's t-test.	The new plane K was found to be both reliable and reproducible. It can be used as a reliable reference plane instead of the Frankfort horizontal plane both clinically and radiographically. It is an accurate tool for head orientation in the natural head position.	Low
	2019	Park J.A., Lee J.S., Koh K.S., Song W.C. [18]	The use of the zygomatic arch as a baseline for clinical applications and anthropological research.	This study aims to establish a new cephalometric measurement to assess the skeletal jaw discrepancy using a new line and plane based on the landmarks of the zygomatic arch where each of them is the upper border. This line is in opposite to the Frankfurt plane.	178 adults aged 21–78 (108 men and 70 women)	The establishment of a more stable and easier to repeat finding of a landmark and horizontal plane compared with the Frankfurt plane.	The intraobserver and interobserver reproducibility of the angular measurements as well as side-related and sex-related differences were analyzed using Student's t test.	The horizontal plane through the Zy point was more stable than the Frankfurt plane. The angle between the Frankfurt plane and the plane through the upper border of the zygomatic arch was also constant: 4.5 degrees ± 2.5 degrees and ranging from −3.3 to 11.9 degrees.	low

6. Results

This section was divided according to answers to Q1 and Q2.

6.1. Q1. New Cephalometric Analysis System in the Sagittal Plane

In the search, a total of 1451 records of articles were identified from the databases. In the first selection stage, 1046 articles were excluded, and another 74 duplicate items were removed. In the end, only 12 articles met the inclusion criteria outlined in the objectives.

6.2. Q2. Cephalometric Analysis Methods in the Horizontal Plane—The Evaluation of Vertical Defects

A total of 1451 records of articles were identified from the database search. In the first selection stage, 1046 articles were excluded. Only 5 articles were included for further analysis of the full text. At this stage, 1 more article was excluded as not meeting the criteria of the objectives. In the end, only 4 articles met the inclusion criteria outlined in the objectives.

7. Discussion of Outcomes

Since Broadbend's and Hofrath's introduction of the cephalometric analysis in 1931, many investigators have introduced further measurements and analyses to assess the skeletal or dentoalveolar basis of malocclusion [27,28]. A detailed cephalometric analysis is still an effective tool for the diagnosis and planning of orthodontic treatment. Unfortunately, like most additional methods of examination, the cephalometric analysis is not free of faults and errors, and thus, it should constitute a component of thoroughly conducted medical interviews and physical examinations to establish final diagnosis and implement the proper treatment of malocclusion. The basis for the systematic search for ever new analyses is the difficulty of mapping landmarks and the dependence of their position on growth and managed orthodontic treatment.

Nowadays, the increasing use and availability of CBCT equipment is largely related to the issue of radiological protection. CBCT is associated with higher radiation dose than OPG or cephalogram. However, if one projection provides the possibility of solving several diagnostic problems, it will replace registration from several projections in favour of one CBCT image. However, in order to be able to perform cephalometric analyses on the CBCT projection, it is necessary to evaluate the accuracy of introducing points such as n image and above all, to develop cephalometric analyses intended for such imaging. As long as such analyses and studies are created, it will be possible to refer them, among others, to the presented systematic review in order to compare the diagnostic value of 2D and 3D cephalometric analyses.

Cephalometric analysis addresses the origin of discrepancies in the sagittal and horizontal planes for the interrelationship of both jaws to identify anterior—posterior and vertical malocclusions [1–8].

The measurements that are the gold standard in terms of the evaluation of sagittal relationships of maxillary bases include ANB angle, beta angle, Wits analysis, AF—BF, MM–AB angle, AH–BH measurement and the Harvold index [7,23,25]. The main objections to the above-mentioned measurements include the instability of the S, N, Po, Or, A and B during growth, changes in their position during orthodontic treatment and the unreliability of their correct location on the cephalometric image that shows the patient's lateral profile (a lateral cephalogram) [7,23,25]. Often, objections arise regarding the correct positioning of anthropometric points by various doctors and even by the same doctor in conducting subsequent analyses of the same patient at time intervals.

The current systematic review takes as its main objective the analysis of new angles and anthropometric measurements used in sagittal and horizontal analyses that were published after 2009. Most publications also discuss several previously used angular and linear measurements that are standards for individual cephalometric analyses, and, based on these analyses, they introduce new anthropometric points and cephalometric measurements [7,23,25].

The Yen angle determined by points S, M, G defines the sagittal relationship between the maxilla and mandible [10].

The measurement of the Yen angle was analysed in a published article by Neela P.K. et al. [10], Kumar and Sundareswaran [23] and Ali et al. [24].

Neela et al. [10] showed more stable sagittal analysis using the Yen angle compared with the previously used Wits, ANB and beta parameters. The elimination of the instability of the A and B points in the ANB analysis in relation to growth and changes due to orthodontic treatment, the functional occlusal plane in Wits and the condylar process axis in the beta angle analysis were considered to be the main advantages of Yen angle assessment.

The evidential value of the study by Neela et al. was found to be moderate, with its main shortcomings being the low number of participants in each group; the lack of comparative studies conducted at a time interval; and the lack of assessment of the stability, reliability and accuracy of the landmarks. The use of statistical analysis based on ANOVA was considered an advantage of the study. The shortcomings shown above indicate that to obtain high evidential value, studies should be conducted on larger groups, using comparative studies in the same study groups in periods before and after orthodontic treatment and by a group of investigators appropriately randomised to assess the reliability of the landmarks used in the analysis, in assessing both between-investigator and intra-observer significance.

Kumar and Sundareswaran [23] also found that the Yen angle is more reliable than the ANB angle, Wits appraisal and beta angle measurement, because it eliminates the difficulty of locating points A and B in ANB analysis, the functional occlusal plane in Wits appraisal and the axis of the condylar process in beta angle analysis. However, the authors point out a shortcoming in the analysis of the Yen angle: When there is rotation of the jaws, the actual sagittal discrepancy may be concealed. The evidential value of the study by Kumar and Sundareswaran was considered low as its main shortcoming was that it only systematised and described in chronological order the cephalometric analyses for assessing the sagittal jaw relationship available in the literature.

The shortcomings shown above indicate that to obtain a high evidential value, comparative studies should be performed for all parameters systematised in a systematic review. Studies should include large study groups, using comparative analysis in the same study groups in periods preceding and following the completion of orthodontic treatment, and be conducted by a group of investigators appropriately randomised to assess the reliability of the landmarks used in each analysis, in assessing both between-investigator and intra-observer significance. In large-scale studies of most cephalometric measurements used to assess sagittal discrepancy, standardised methodological criteria and comparisons of the significance of individual measurements using the same statistical analysis should be used for effective comparison.

Turker, Ozturk, Coban and Isgandarov [8] confirmed the validity of using Yen angle. In high-angle patients, Yen was found to be significantly lower than in low-angle patients and comparable with Pog–Nperp and Wits analysis in relation to beta angle, which was found to be significantly higher in this group. Beta and W angles were significantly lower in LA patients compared with HA patients. ANB, Beta, W and Yen angles showed significant correlations regardless of vertical facial growth type. The comparison of Yen angle analysis with other analyses in relation to the horizontal plane and vertical defects and the use of adjusted ANOVA were considered attributes of the presented study.

A comparison of only some parameters, without any indication of the selection criteria, was considered its fundamental shortcoming.

In order to obtain high evidential value, it would have been necessary to clarify the criteria for selecting the parameters to be assessed and to allow the comparison of the determinations of measurement values by different observers as well as by the same observer in comparative studies.

Ali et al. [24] showed reservations about the effectiveness of using the Yen angle in sagittal analysis. The authors showed that comparing beta, Yen and W angles with ANB angle and Wits appraisal does not show statistically significant differences in class III patients. A total of 100 lateral cephalograms were included in the study, and the use of only t-student statistical analysis was the shortcoming of this study. For this reason, the evidential value of the work was considered moderate. To increase the value of the evidence, it would have been necessary to use an advanced statistical method and determine whether the lack of statistically significant differences was only in Class III patients or whether the use of Yen angle analysis deviates from ANB, beta and W angle analyses and Wits appraisal in all skeletal classes determined in their comparison.

On the basis of the above studies, the use of Yen angle in the cephalometric analysis of sagittal discrepancy can be considered a valuable parameter because it is less dependent than the previously used ANB and beta angle and Wits appraisal to complement previous assessments.

7.1. Pi Analysis

Pi analysis was first taken into account by Kumar, Valiathan, Gautam, Chakravarthy and Jayaswal [12]. Pi analysis was also applied by Shetty, Desai, Kumar, Madhur and Alphonsa [26] and Kumar and Sundareswaran [23].

Kumar et al. [12] showed that the M and G landmarks used in Pi analysis are less susceptible to local changes associated with remodelling during growth or to secondary movements associated with remodelling during orthodontic treatment compared with A and B landmarks. The authors showed that the centroidality of the landmarks affects the precision of their determination and their invariability during growth, in contrast with previous standards such as A and B. The use of the true horizontal plane obtained in the NHP used in Pi analysis instead of another intracranial reference plane (SN, Frankfurt plane or occlusal, which have some specific limitations) results in the increased reliability of measurements. They showed that the comparison of NG' with NM' with normative values determines whether the defect originated from the maxilla or the mandible.

A limitation of Pi analysis is that it considers the position of the nasion during the growth period, which may change during actual jaw growth.

The evidential value of the study by Kumar et al. was found to be moderate. The main shortcomings of the above-mentioned study were the low number of participants in each group; the lack of comparative studies conducted at a time interval; and the lack of assessment of the stability, reliability and accuracy of the landmarks. The use of ANOVA was considered an advantage of the study. The demonstrated shortcomings indicate that for a high level of evidential value, studies should be conducted on larger groups using comparative analysis in the same study groups in the periods preceding and following the completion of orthodontic treatment and be conducted by a group of investigators appropriately randomised to assess the reliability of the landmarks used in each analysis, in assessing both between-investigator and intra-observer significance.

Pi analysis was included in a systematic review of 21 analyses for the assessment of anteroposterior discrepancy by Shetty et al. [26].

The evidential value of the study by Shetty et al. was considered low. The main shortcoming of the study was the systematic evaluation of only the individual parameters of sagittal discrepancy and not taking into account the criteria and evaluation of individual parameters on specific groups of subjects.

An advantage of the conducted study was the systematisation of known parameters for the assessment of sagittal discrepancy.

The demonstrated shortcomings indicate that for a high level of evidential value, studies should be conducted by randomised observers comparing the values of individual parameters for the assessment of maxillary base relationships in numerous groups of subjects before and after orthodontic treatment, assessing the rank of the suitability of individual parameters for the assessment of maxillary–mandibular relationships.

Kumar and Sundareswaran [23] also found that the Pi analysis is more dependable than ANB angle, Wits appraisal and beta angle because it eliminates the difficulty of locating points A and B in ANB analysis, the functional occlusal plane in Wits appraisal and the axis of the condylar process in beta angle analysis. In their discussion of cephalometric analyses in relation to Pi analysis, the authors stated that the highest level of correlation was obtained only for Pi angle and Pi linear (0.96)

The study presented here showed that Pi analysis, related to both the evaluation of Pi angle and the Pi linear measurement in determining the sagittal relationships of the maxilla and mandible, is a more objective analysis than the evaluation of the ANB angle, Wits appraisal or beta angle analysis.

7.2. Analysis of W Angle Determined by Points S, M, G Defining the Sagittal Relationship between the Maxilla and Mandible. W Angle Measured between the Line Perpendicular to Point M on SG Line and MG Line

W angle analysis was taken into account by Bhad, Nayak, Doshi [13], Kumar and Sundareswaran [23], Ali et al. [24], Shetty et al. [26] and Turker et al. [8].

Bhad et al. [13] also showed the higher stability of sagittal analysis using W angle compared with the previously used Wits, ANB and beta parameters. The elimination of the instability of the A, B and N points in the ANB analysis in relation to the growth and changes due to orthodontic treatment, the functional occlusal plane in Wits and the condylar process axis in beta angle analysis were considered to be the main advantages of W angle assessment. In the analysis of W angle, points S, G and M were used. By replacing the N point, which is unstable in the growth phase, with the S point, they proved that W angle measurement is more stable for the assessment of sagittal discrepancy than ANB angle, Wits analysis or beta angle.

The evidential value of the study by Bhad et al. was considered moderate, as the main shortcomings of this study were the low number of participants in each group; the limitation of the study to only a group that had not yet received orthodontic treatment without comparison with the stability of the results after the treatment; the lack of comparative studies at an interval; and the lack of assessment of the stability, reliability and accuracy of the landmarks. The use of ANOVA was considered an advantage of the study.

Kumar and Sundareswaran [23] also found that W angle analysis is more reliable compared with ANB angle, Wits appraisal and beta angle because it eliminates the difficulty of locating points A, B and N in ANB analysis, the functional occlusal plane in Wits appraisal and the axis of the condylar process in beta angle analysis. In discussing cephalometric analyses in relation to W angle analysis, the authors noted a statistically significant difference between W angle measurement values in men and women for Class III diagnosis.

Ali et al. [24], in their comparative study, indicated that W angle analysis is the closest to ANB angle and Wits appraisal in Class I defects. In Class II and III defects, the authors questioned the effectiveness of assessing the sagittal relationship of the jaws based on W angle analysis. They claimed that it is less satisfactory compared with ANB, beta and Wits, which are considered standard. In their review, the authors considered the ANB angle to be the gold standard in the assessment of sagittal discrepancy.

The evidential value of the study by Ali et al. was considered moderate. Its main shortcomings were the small size of the study group, the limitation of the study to patients whose orthodontic treatment has not yet been initiated, the use of the t-student test as the only statistical tool, the lack of comparative studies and the lack of the comparative assessment of inter-observer and intra-observer stability of landmarks.

Shetty et al., in their systematic review of 21 studies assessing anteroposterior discrepancy, confirmed the value of using W angle analysis [26].

The study presented here showed that the analysis of W angle in determining the sagittal relationship between the maxilla and mandible is more objective than the assessment of the ANB, Wits or beta angle, although ANB, Wits and beta are considered by some authors to be the gold standard in the assessment of the sagittal relationship.

7.3. SAR Angle

SAR angle measurement was analysed in a study by Sonahita et al. [14], Kumar and Sundareswaran [23] and Shetty S. et al. [26].

Sonahita et al. [14] proved that M, G and W used in the analysis are more stable and reliable as they are easier to find compared with A, B and N and do not undergo changes due to growth and transformations associated with orthodontic treatment. Therefore, SAR analysis was demonstrated to have higher reliability than ANB, beta and Wits analyses.

The evidential value of the study by Sonahita et al. was found to be moderate since the main shortcomings of the above-mentioned study were the low number of participants in each group; the lack of comparative studies conducted at a time interval; and the lack of assessment of the stability, reliability and accuracy of the landmarks. The use of ANOVA was considered an advantage of the study. The demonstrated shortcomings indicate that for a high level of evidential value, studies should be conducted on larger groups, using comparative analysis in the same study groups in periods preceding and following the completion of orthodontic treatment and be conducted by a group of investigators appropriately randomised to assess the reliability of the landmarks used in each analysis in assessing both between-investigator and intra-observer significance.

Kumar and Sundareswaran [23] also found that SAR angle analysis is more reliable than ANB, Wits and beta because it eliminates the difficulty of finding A, B and N points in ANB analysis. In their conclusion, the authors emphasised that the rotational effects of the jaws; the variable positions of A, B and N; changes in the length of the skull base; tooth eruption; the curve of Spee, etc. seem to affect the assessment of the position of the mandible in relation to the maxilla, which also results in the use of extracranial reference planes. At the same time, using only one of the cephalometric analyses may not provide a correct diagnosis. Therefore, for a correct diagnosis, several of the angular or linear parameters should be used without considering only one type of measurement as being the only valid one in assessing the relationship to the jaw.

Shetty et al. [26], in their systematic review of 21 studies assessing anteroposterior discrepancy confirmed the value of using SAR angle analysis [26] The authors came to similar conclusions as Kumar and Sundareswaran. In their conclusion, they emphasized that rotational effects of the jaws, variable positions of points A and B, nasion, changes in skull base length, tooth eruption, curve of Spee etc., seem to affect the assessment of the position of the mandible in relation to the maxilla which also results in the use of extracranial reference planes. At the same time, using only one of the cephalometric analyses may not provide a correct diagnosis. Therefore, for a correct diagnosis, several of the angular or linear parameters should be used without considering only one type of measurement as being the only valid one in assessing the relationship to the jaw.

In their conclusion, the authors emphasised that the rotational effects of the jaws, the variable positions of points A, B and nasion, changes in the length of the skull base, tooth eruption, the curve of Spee, etc., seem to affect the assessment of the position of the mandible in relation to the maxilla which also results in the use of extracranial reference planes. At the same time, using only one of the cephalometric analyses may not provide a correct diagnosis. Therefore, for a correct diagnosis, several of the angular or linear parameters should be used without considering only one type of measurement as being the only valid one in assessing the relationship to the jaw.

Based on the study presented here, the value of SAR angle analysis as a parameter helpful in assessing sagittal discrepancy and the position of the maxillary bases should be recognised.

7.4. DW Angle Using Walker's and Wing (WW) Point

DW plane measurement has been analysed in a study by Hatewar et al. [15], Kumar and Sundareswaran [23] and Shetty et al. [26].

Hatewar et al. [15] showed significant regularity in the evaluation of the sagittal relationships of jaw bases. The measurements so far considered to be authoritatively established for the assessment of the sagittal relationship often turn out to be inaccurate because they are based on various angular and linear measurements related to the position of N, A and B points. The landmarks used in the DW analysis are characterised by higher stability and repeatability, reliability and invariability in relation to growth processes and changes resulting from orthodontic treatment, in contrast to N, A and B, which increases the unambiguity of the measurements. In DW plane analysis, linear measurements are performed to determine the vertical mandibular dimension, and angular measurements are taken to determine the rotation of the jaw.

The evidential value of the study by Hatewar et al. was found to be moderate as the major drawbacks of this study include the low number of participants in each group; limitation of the study to one race without interracial comparison; no comparison studies made at time intervals; no assessment of the stability, reliability and accuracy of landmarks; ad the use of Student's *t*-test statistical method only. The use of the analysis in different age groups from 8 to 27 years was considered an advantage for the study.

The demonstrated shortcomings indicate that for a high level of evidential value, studies should be conducted on larger groups, using comparative analysis in the same study groups in periods preceding and following the completion of orthodontic treatment and be conducted by a group of investigators appropriately randomised to assess the reliability of the landmarks used in each analysis, in assessing both between-investigator and intra-observer significance. Moreover, an extensive statistical analysis based on ANOVA should be applied.

The evidential assessment makes it possible to conclude that measurements relative to the DW plane are more effective compared with the ANB, Wits or beta measurements that are routinely used for assessing sagittal discrepancy.

7.5. Tau Angle

The measurement of Tau angle was analysed by Gupta, Singh, Tripathi, Gopal, and Rai [6].

The Tau angle determined by points T, M, G and defining the sagittal relationship between the maxilla and mandible.

The authors found higher precision and reliability in the assessment of jaw sagittal relationships by using points G and M, with higher invariance than A and B, and Tau point that is more reliable than S compared to routinely used ANB and Beta angle analyses and Wits analysis. The authors indicate that the obtained results define a skeletal ratio that depends on stable landmarks. At the same time, they reveal that the assessment is not affected by jaw rotation in the vertical dimension due to growth or implemented orthodontic treatment.

The evidential value of the study by Gupta et al. was considered moderate. The main shortcomings of the study include the inequality of various groups of participants; the large age range of the patients studied in one group that included both adolescent and adult patients; the lack of comparative studies before and after orthodontic treatment; the lack of comparative studies made at time interval; and the lack of an assessment of stability, reliability and accuracy of landmarks. The use of ANOVA was considered an advantage of the study.

The demonstrated shortcomings indicate that for a high level of evidential value, studies should be conducted on larger age-equivalent groups, using comparative analysis in the same study groups in periods preceding and following the completion of orthodontic treatment, and be conducted by a group of investigators appropriately randomised to assess the reliability of the landmarks used in each analysis, in assessing both between-investigator and intra-observer significance. It seems necessary to confirm the dependence of evaluated parameters on rotation of the mandible and maxilla that are related to the patient age.

Only one study does not enable firm conclusions supporting the reliability of the Tau angle analysis in assessing sagittal discrepancy and requires further research.

7.6. R Angle

The R angle was measured by Rizwan, Mascarenhas [16], Ahmed, Shaikh and Fida [25]. It is determined by points N, C and Me [16].

Rizwan et al. [16] proved that the R angle is constructed from minimal cephalometric landmarks that can be easily and accurately located on digital lateral cephalograms. Over them, the R angle is constructed using only fixed skeletal landmarks and no constructed points or landmarks, thereby minimising operator error. The C–N axis and C–Me axis are more stable compared with the currently used unstable planes.

A systematic description of various cephalometric measurements compared with vertical defects is favourable for the study. Attention should be paid to a chronological review of methods for assessing vertical discrepancy and a discussion concerning the reliability and shortcomings of various anthropometric points, lines and planes, as well as the skewed values of parameters used for assessing vertical defects.

The evidential value of the study by Rizwan et al. was considered moderate. The main shortcomings of the study include the low number of participants; the specified and limited ages of the participants (18–27 years); the lack of comparative studies before and after the orthodontic treatment; the lack of comparative studies made at time intervals; and the lack of the assessment of stability, reliability and accuracy of landmarks. The use of statistical analysis based on ANOVA was considered an advantage of the study.

The demonstrated shortcomings indicate that for a high level of evidential value, studies should be conducted on larger age-equivalent groups, using comparative analysis in the same study groups in periods preceding and following the completion of orthodontic treatment, and be conducted by a group of investigators appropriately randomised to assess the reliability of the landmarks used in each analysis, in assessing both between-investigator and intra-observer significance. There should also be comparisons of the reliability of the lines that represent the size of the angle at different development stages of patients from selected high-, medium- and low-angle skeletal groups.

A comparative evaluation of the R angle was also made by Ahmed, Shaikh and Fida [25].

The authors denied the value of the R analysis in assessing vertical discrepancy. In the light of obtained results, the authors proved that SN.GoGn and FMA are the most reliable indicators, while LAFH.TAFH turned out to be the least reliable indicator in assessing the vertical facial growth pattern.

Given that the article discusses the results of twice as many participants in each vertical discrepancy group, its evidential value can be considered higher than the results of the study by Rizwan M. et al.

The evidential value of the study by Ahmed et al. was considered moderate. The main shortcomings of the study include the low number of participants; the lack of comparative studies before and after orthodontic treatment; the lack of comparative studies made at time intervals; and the lack of the assessment of stability, reliability and accuracy of landmarks. The use of statistical analysis was considered an advantage of the study. Kappa statistics were used for comparing the diagnostic accuracy of different analyses. To further validate the results, sensitivity and positive predictive value (PPV) were calculated for each parameter.

The demonstrated shortcomings indicate that for a high level of evidential value, studies should be conducted on larger age-equivalent groups, using comparative analysis in the same study groups in periods preceding and following the completion of orthodontic treatment and be conducted by a group of investigators appropriately randomised to assess the reliability of the landmarks used in each analysis in assessing both between-investigator and intra-observer significance. There should also be comparisons of the reliability of the lines that represent the size of the angle at different development stages of patients from selected hyperdivergent, normodivergent and hypodivergent skeletal groups.

The conflicting results of published studies need repeated and more detailed research to make constructive conclusions about the usefulness of R angle analysis in assessing vertical relationships.

7.7. KP Plane (Extraoral)

The measurement of the KP plane was analysed by Kattan, Kattan and Elhiny [17].

An innovation in the creation of plane K is the use of an extraoral orientor when taking a 2D cephalogram to determine the natural head position (NHP).

The authors found a high correlation with the Frankfurt plane; however, due to the higher reliability and accuracy of the determination of the new plane K, the obtained results of the vertical discrepancy measurements give results that are similar to real values, minimising the risk of error that is associated with the determination of Po and Or points.

The correct assessment of plane K was dependent on NHP and the positioning of the orientor to stabilise the head in its natural position.

The authors noted that the suggested position can be used for two-dimensional radiography and computed tomography.

The authors' conclusion is that determination of the plane K compared to the Frankfurt plane is much more reproducible and accurate in cephalometric analysis, especially when using an orientor for head orientation in NHD. The introduction of plane K gives an advantage over previous analyses by introducing an additional stable orientor for the correct orientation of the patient's head in NHP.

The evidential value of the study by Kattan et al. was considered moderate. The main shortcomings of the study include the low number of participants; the lack of comparative studies before and after orthodontic treatment; the lack of comparative studies made at time intervals; and the lack of the assessment of stability, reliability and accuracy of landmarks, as well as the lack of unbiased statistical analysis.

The demonstrated shortcomings indicate that for a high level of evidential value, studies should be conducted on larger age-equivalent groups, using prospective, retrospective and comparative studies in the same study groups in periods preceding and following the completion of orthodontic treatment and be conducted by a group of investigators appropriately randomised to assess the reliability of the landmarks used in each analysis in assessing both between-investigator and intra-observer significance. It would be advisable to study a larger number of groups and to compare results at different development periods.

A further analysis and additional tests are necessary to determine diagnostic values of plane K.

7.8. The Superior Border of Zygomatic Arch

The effectiveness of the use of a plane A, the superior border of the zygomatic arch, was proved by Park, Lee, Koh and Song W.C. [18].

The study was developed using 3D cone–beam computed tomography. A 3D–2D transcription seems possible, although this would require further research.

The authors revealed that the proposed new plane of the zygomatic arch may be an alternative plane to the Frankfurt line but more reliable for the assessment of vertical discrepancy.

The applied analytical and statistical methods proved the stability of the measurement between the Frankfurt line and the zygomatic arch line.

The evidential value of the study by Park et al. was considered moderate. The main shortcomings of the study include the low number of participants, limiting the age of participants to 21–30 years, the use of only 3D examinations, the lack of comparative studies before and after orthodontic treatment; the lack of comparative studies made at time intervals; and the lack of the assessment of stability, reliability and accuracy of landmarks, as well as the lack of unbiased statistical analysis, which was limited to the Student's t-test analysis.

The demonstrated shortcomings indicate that to obtain a high degree of evidential value, 2D examinations should be conducted, groups should be larger and age-equivalent and examinations should be conducted in different age groups including groups of patients in the developmental period. Moreover, comparative studies should be carried out in the same study groups in periods before and after orthodontic treatment.

A further analysis and additional tests are necessary to determine diagnostic values of the plane of the zygomatic arch.

8. Conclusions

The evidence suggests that there are many new reference points and cephalometric indices that can be successfully used for determining the sagittal discrepancy in the mutual position of the maxillary bases. However, although the systematic review has low heterogeneity, the included studies exhibited a moderate risk of bias and low to moderate quality. Future studies are required with adequate internal and external validity. Sagittal discrepancy and assessment methods of the relationship between the upper jaw and lower jaw should be more accurate in the future.

In terms of the new cephalometric measurements to determine discrepancy in the vertical dimension, the number of performed studies is limited, with very low quality and moderate risk of bias of the study assessed. Simultaneously, the review revealed the existence of novel alternative parameters to contemporary measurements in 3D examinations. Tracing the process of determining reference points, lines and anthropometric planes in volumetric tomography also seems possible in 2D. However, such suggestions require further research and analysis. Current studies do not seem to be very constructive.

Due to the radiological protection of patients and the tendency to limit exposure to X-rays, it seems necessary to use 2D cephalometric diagnosis and, only in borderline cases, 3D diagnosis.

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8.2. Publikacja 2

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Article

Comparison of Diagnostic Validity of Cephalometric Analyses of the ANB Angle and Tau Angle for Assessment of the Sagittal Relationship of Jaw and Mandible

Jacek Kotula [1,*], Anna Kuc [1], Ewa Szeląg [1], Alicja Babczyńska [1], Joanna Lis [1], Jacek Matys [2,3,*], Beata Kawala [1] and Michał Sarul [1]

[1] Department of Dentofacial Orthopedics and Orthodontics, Wroclaw Medical University, Krakowska 26, 50-425 Wroclaw, Poland; dental.star@wp.pl (A.K.); ewa.szelag@umw.edu.pl (E.S.); ortodoncja@umw.edu.pl (A.B.); joanna.lis@umw.edu.pl (J.L.); beata.kawala@umw.edu.pl (B.K.); michal.sarul@umw.edu.pl (M.S.)
[2] Oral Surgery Department, Wroclaw Medical University, Krakowska 26, 50-425 Wroclaw, Poland
[3] Department of Orthodontics, Technische Universitat Dresden, 01307 Dresden, Germany
* Correspondence: j_kotula@poczta.onet.pl (J.K.); jacek.matys@umw.edu.pl (J.M.)

Abstract: Background: Cephalometric analysis is an essential tool used in orthodontic diagnosis and treatment planning. The aim of this study was to evaluate the reliability and repeatability of new cephalometric points introduced in Tau angle analysis, in contrast to the gold standard, which is the analysis of the ANB angle. For this purpose, an attempt was made to assess the repeatability and reliability of the introduction of anthropometric points by evaluating both inter- and intraobserver parameters, as well as the agreement among the orthodontists participating in the study. Methods: Repeatability and reliability assessments for all six anthropometric points (N, A, B, T, M, G) used in the analysis of the ANB and Tau angles were conducted individually by 29 orthodontists. This assessment was performed in triplicate on the day of the study, on the day following the first study, and on the seventh day after the second study. Measurement errors for the ANB and Tau angles were evaluated using the Dahlberg formula and intraclass correlation coefficients (ICCs). Results: The orthodontists in the study measured sagittal discrepancy significantly more accurately using the ANB angle compared to the Tau angle ($p < 0.001$). The Dahlberg error for measuring the Tau angle was three times greater than that for the ANB angle ($p < 0.001$). Additionally, the ICC for the Tau angle was more than 3.5 times smaller than that for the ANB angle, while the R&R error for Tau measurement was more than three times greater than that for the ANB angle ($p < 0.001$). Conclusions: The results of ANB angle measurements exhibit fewer errors in comparison to Tau angle measurements.

Keywords: cephalometric analyses; diagnosis; orthodontics

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1. Introduction

Orthodontic treatment planning relies on the accurate diagnosis of skeletal discrepancies, necessitating precise cephalometric parameters. Cephalometric analysis serves as a crucial tool in assessing the sagittal dimension and compatibility of mandibular–maxillary bases [1,2]. To ensure the reliability of diagnostic data obtained through cephalometric analysis, it is imperative to maintain stability, clarity, and repeatability in landmark identification, as well as in linear and angular measurements [2].

In 2022, a new systematic review was published, which included new linear and angular measurements to assess the sagittal discrepancy of maxillary bases [1]. Few studies utilizing new methods of cephalometric evaluation have been published in recent years. An example of such an approach is the Tau method developed by Gupta et al. [3]. This angle is determined by three T landmarks (new landmarks), as well as G and M points, which form T–G and G–M auxiliary lines. The Tau angle is measured between them, identifying the mandibular position in relation to the maxilla in the sagittal dimension. The development of this new analysis, used for determining the sagittal position of the maxillary bases in relation to each other, has raised numerous objections related to the stability and repeatability of previous cephalometric parameters. The authors made efforts to address issues with the repeatability of cephalometric parameter analyses, which, among other things, are associated with the following:

1. ANB angle stability due to growth changes and the instability of the position of point N, which affects the size and clarity of the ANB angle during growth [4,5].
2. Changes in the measurement of the length of the skull base, which affects the ANB angle [4,5].
3. Rotation of the condyle at the temporomandibular joint, which influences changes in the sagittal relationship between the maxillary bases in relation to each other and the rotation of the mandible during orthodontic treatment.
4. Wits assessment [5], which is related to the instability of the occlusal plane. It can be challenging to accurately determine the precise occlusal plane at various stages of tooth development and dental age. The irregularity of the occlusal plane is also influenced by factors such as missing teeth, malocclusions, and mandibular deformities.
5. Assessment of the W angle, which is measured between the perpendicular line to point M on the SG line and the MG line [6]. Although W angle analysis utilizes points M and G (the same points used in Tau angle analysis), which are relatively stable and do not undergo relocation due to remodeling associated with tooth movements, the S point, on the other hand, is highly unstable as it moves backward and downward during growth.
6. Imprecision and difficulty of determining the Beta angle [7]. The Beta angle is the angle formed by the perpendicular line drawn from point C to point A, intersecting with the line AB. This angle utilizes three distinctive skeletal elements—point A, point B, and the prominent condylar axis—to measure an angle that indicates the severity and type of skeletal dysplasia in the sagittal dimension [8]. Beta angle analysis relies on point A as a landmark, and changes in its position are associated with alveolar remodeling resulting from orthodontic movements. Additionally, determining the position of the mandibular condyle can be challenging, which consequently limits the reliability of the Beta angle.
7. YEN angle assessment [9] is based on landmarks such as S, M (midpoint of the anterior maxilla), and G (center at the bottom of the symphysis), which together form the YEN angle measured at point M. Points M and G are the same as those used in Tau angle analysis. The imprecision arises from the fact that point G shifts in a manner resembling the letter 'S' during growth.

The authors of the Tau angle method consider the location of the center of the maxilla and the mandibular symphysis as precise and appropriate compared to other reference points in the analysis of sagittal discrepancy of the maxillary bases, and as more stable compared to points N and S in the correct assessment of the sagittal discrepancy of the designated T point [3]. The T point is located at the highest point at the junction of the frontal wall of the pituitary fossa and the tuberculum sellae. The M and G points are also stable. Analysis of the Tau values between 28° and 34° suggests skeletal Class I malocclusion; values below 28° indicate skeletal Class III, and those above 34° suggest skeletal Class II [3]. However, as mentioned above, each cephalometric measurement is only of diagnostic value if the points that define it are easily determined in a clear and repeatable manner using a digital image. Moreover, the introduction of a new measurement only makes sense if its use either enables the diagnosis to be made in a clearer, more confident manner or enables other diagnostic benefits to be achieved.

Orthodontic treatment planning is based on the correct diagnosis of skeletal discrepancy, which requires accurate and precise cephalometric parameters. This article aims to assess the measurement accuracy of two cephalometric angles (ANB—the gold standard in the sagittal discrepancy analysis—and the new Tau angle) based on nine cephalograms of patients differing in terms of skeletal class.

The aim of selecting cephalometric images with typical skeletal classes was to assess whether the accuracy and repeatability of determining anthropometric points, and, thus, the results of internal sagittal analysis in all configurations, are comparable, or whether the skeletal discrepancy affects the reliability of the entered points and measurements.

2. Materials and Methods

This study was approved by the Bioethical Committee at the District Medical Chamber in Zielona Góra, decision no. 01/173/2023 of 6 March 2023, and informed consent in accordance with the Declaration of Helsinki was obtained from all participating subjects/their parents. The sample size of 29 orthodontists/observers was calculated using G*Power (Kiel University, Germany) software based on preliminary measurements with a significance level of 0.05, d = 0.5, 95% confidence intervals, and 83% power. All subjects were selected to meet the inclusion criteria, representing patients before orthodontic treatment with various Angle Class I, Class II, and Class III categories characterized by different base angles, while also meeting conditions of being free from systemic illnesses, or untreated dental and periodontal disease.

The authors evaluated the reliability of lateral cephalograms and their ANB angle cephalometric analysis in correlation with the newly introduced Tau angle analysis, which was not present in the scientific literature prior to the conclusion of 2021 [1,3] (Figures 1 and 2).

Figure 1. The landmarks T,M,G used in Tau angle analysis.

Cephalometric radiographs were taken with the patient's head correctly fixed in a cephalostat. Oils were inserted centrally into the external ear canals. The correctness of a beam path perpendicular to the sagittal plane was verified. The head was positioned in such a way that the Frankfort horizontal plane was parallel to the floor. Patients were advised to grit their teeth in central occlusion and have a slightly closed mouth.

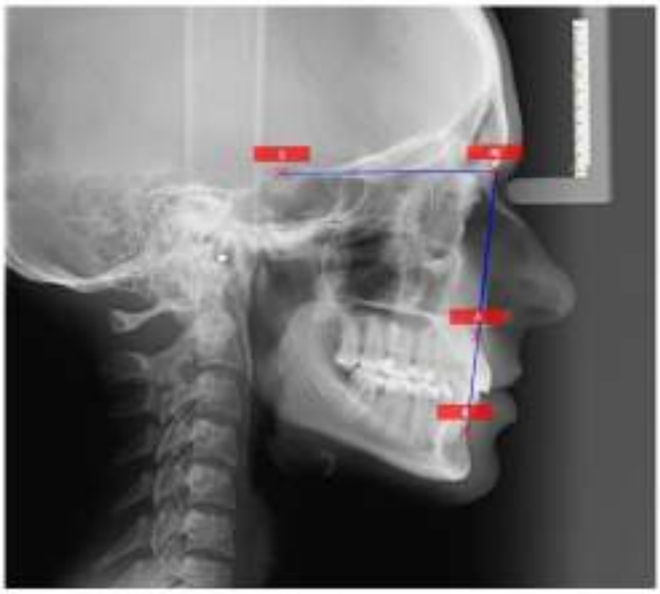

Figure 2. The landmarks used in ANB analysis.

The position of the six cephalometric points was determined on 9 radiographs. These were the coordinates of the N, A, B, T, M and G points from which ANB and Tau were determined. The software Orthodontics v. 9 was used for determining the coordinates of the points and calculating the angles. Analyses were performed using NEC Multisync EA 244 WMi (NEC, Tokyo, Japan) medical monitors, certified by the Diagnostic Equipment Quality Laboratory.

Finally, 9 cephalometric radiographs of patients before orthodontic treatment were used for the study:

- Cephalogram 1, showing Angle Class I patient "A" with a high base angle;
- Cephalogram 2, showing Angle Class I patient "D" with an average base angle;
- Cephalogram 3, showing Angle Class I patient "E" with a low base angle;
- Cephalogram 4, showing Angle Class II patient "B" with a high base angle;
- Cephalogram 5, showing Angle Class II patient "F" with an average base angle;
- Cephalogram 6, showing Angle Class II patient "G" with a low base angle;
- Cephalogram 7, showing Angle Class III patient "C" with a high base angle;
- Cephalogram 8, showing Angle Class III patient "H" with an average base angle;
- Cephalogram 9, showing Angle Class III patient "I" with a low base angle.

The assessment of 450 images was performed independently by two authors of this article (J.K., A.E.K.)—only correctly taken cephalograms were used. The authors initially conducted a cephalometric analysis following the Segner Hasund method to categorize the photos into the appropriate groups based on the specified criteria. The following exclusion criteria were used:

1. The presence of asymmetry that is visible on the radiograph and is interpreted as greater than 10% divergence of contours of the right and left mandibular bases;
2. Landmarks on cephalograms that could not be identified due to a projection error or an incorrect contrast;
3. Bilateral anatomical structures that did not overlap properly by superimposing on the mediolateral plane.

From this selected group of cephalograms, one cephalogram was chosen for each of the 9 patient groups mentioned earlier, matching the appropriate Angle Class and angle of the maxillary bases. Twenty-nine orthodontists were invited to participate in the study and received initial training on accurately identifying anthropometric points for both the ANB angle and the Tau angle. Each researcher conducted the ANB and Tau angle analyses three times, on days 0, 1, and 7.

The landmark identification was carried out manually on digital images using a cursor controlled by a computer mouse. The results were recorded in an Excel spreadsheet (Microsoft, Seattle, WA, USA). Subsequently, statistical analysis was conducted. The mean and standard deviation of the Tau angle for each of the 9 cephalograms, related to individual skeletal defects in the sagittal plane, were measured in correlation with the size of the base angles to assess the stability of the Tau angle in evaluating skeletal defects. The obtained values were then correlated with parameters from the ANB angle analysis.

In total, six cephalometric points were identified on each of the 9 radiographs. These points consisted of coordinates for the N, A, B, T, M, and G points, which were used to determine the ANB and Tau angles in patients before orthodontic treatment. This analysis was conducted by a lead researcher and 28 randomly selected observers, all of whom were orthodontists. Digital contours and measurements were collected in triplicate on the day of the study, on the day following the initial study, and on day 7 following the second study. The positions of landmarks determined by the 29 observers were assessed in relation to the x-axis (horizontal divergence) and the y-axis (vertical divergence) as mean values and standard deviations (Figures 1 and 2).

The reliability of the method, signifying the significance of the relationship between the coordinates of the points included in determining cephalometric angles, was assessed using the Pearson correlation coefficient (r^2). The level of statistical significance was set at $p < 0.05$. The repeatability between methods was calculated by determining errors using Dahlberg's formula and assessing interclass and intraclass correlation coefficients (ICCs). Intraclass correlation coefficient values were interpreted according to Koo and Li [10]. The evaluation of the repeatability and reproducibility of measurements was based on the variability (variance) of the coordinates of designated points. The assessment was divided into the following three groups:

- Variability in the position of cephalometric points among the group of 9 studied patients (between-group variance);
- Variability in the position of cephalometric points made by 29 different doctors (reproducibility);
- Measurement errors across three measurements made by the same doctor on the same patients (repeatability).

The R & R (Repeatability and Reproducibility) module of STATISTICA v.13.3 (TIBCO Software Inc., Palo Alto, CA, USA) was utilized for the analysis of repeatability and reproducibility. When analyzing ANB and Tau values for assessing the correct classification of patients into one of three skeletal classes, the Cohen's kappa coefficient was used. Cohen's kappa is the reliability coefficient for measuring the same variable twice, which is the nominal and dependent variable. Cohen's kappa takes values from −1 to 1. The closer the value is to 1, the more concordant the assessments are when using the two methods.

3. Results

The mean values presented in the analysis were calculated from a comprehensive dataset encompassing a total of 87 measurement results. These results were obtained through the combined measurements of 29 different doctors, each performing three repetitions of measurements for both the ANB and Tau angles. The measurements were conducted using the coordinates associated with points A, N, B, T, G, and M, ensuring a thorough and robust assessment of these cephalometric angles (Table 1).

Table 1. Mean and standard deviation values of the ANB and Tau angles.

Patient	Class	ANB (°) M ± SD	Tau (°) M ± SD
A	I	2.2 ± 0.4	33.0 ± 1.5
B	II	5.7 ± 1.0	40.4 ± 2.2
C	III	0.2 ± 1.9	27.7 ± 4.2
D	I	4.7 ± 1.1	33.1 ± 2.5
E	I	1.3 ± 1.0	34.3 ± 2.0
F	II	7.1 ± 2.4	38.6 ± 3.5
G	II	5.3 ± 1.5	37.6 ± 2.7
H	III	−1.8 ± 1.6	25.8 ± 2.5
I	III	−0.7 ± 0.6	26.2 ± 2.2

The first digit is the average value, and the +/− sign is followed by the standard deviation (M ± SD—mean and standard deviation).

3.1. *ANB Angle*

The ANB angle is determined by the coordinates of points A, N, and B, and it can be calculated according to the following relationship:

$$ANB = \text{arc tg}[(N_y - A_y)/(N_x - A_x) - (N_y - B_y)/(N_x - B_x)]/[1 + (N_y - A_y)/(N_x - A_x) * (N_y - B_y)/(N_x - B_x)]$$

Therefore, the accuracy of the ANB angle identification depends on the location accuracy on the cephalograms of points A, N, and B. Table 2 shows the mean values obtained from 87 measurement results (29 doctors × 3 repetitions) for the ANB angle and coordinates of points A, N, and B. The A and B dispersions are vertical (variability is greater in the direction of the vertical axis $A\Delta A_x$), while N dispersion is concentric (variability in both directions is of the same order). The location accuracy of the horizontal coordinates of points A, N, and B is approximately twice that of the vertical coordinates. The accuracy of the ANB angle measurement is most affected by the accuracy of the horizontal location of points A (A_x coordinate) and B (B_x) and both coordinates of point N (Table 3).

Table 2. Mean and standard deviation values of the ANB angle and coordinates of points A, N, and B measured on 9 cephalograms three times by 29 doctors (n = 87).

Patient	Class	ANB (°)	Point A		Point N		Point B	
			A_x (cm)	A_y (cm)	N_x (cm)	N_y (cm)	B_x (cm)	B_y (cm)
A	I	2.2 ± 0.4	5.99 ± 0.01	2.73 ± 0.04	5.97 ± 0.01	4.61 ± 0.02	5.89 ± 0.01	1.75 ± 0.03
B	II	5.7 ± 1.0	4.67 ± 0.02	2.67 ± 0.03	4.67 ± 0.01	4.56 ± 0.01	4.41 ± 0.02	1.99 ± 0.07
C	III	0.2 ± 1.9	5.04 ± 0.01	2.50 ± 0.05	5.00 ± 0.03	4.38 ± 0.08	5.08 ± 0.01	1.27 ± 0.04
D	I	4.7 ± 1.1	5.28 ± 0.04	3.29 ± 0.09	5.13 ± 0.01	5.20 ± 0.02	5.12 ± 0.01	1.93 ± 0.07
E	I	1.3 ± 1.0	5.92 ± 0.01	2.89 ± 0.04	5.96 ± 0.01	4.80 ± 0.02	5.83 ± 0.01	1.81 ± 0.04
F	II	7.1 ± 2.4	4.36 ± 0.02	2.77 ± 0.05	4.38 ± 0.01	4.52 ± 0.01	3.95 ± 0.01	1.64 ± 0.03
G	II	5.3 ± 1.5	5.90 ± 0.01	2.38 ± 0.04	5.96 ± 0.02	4.19 ± 0.08	5.61 ± 0.01	1.53 ± 0.06
H	III	−1.8 ± 1.6	7.29 ± 0.03	3.86 ± 0.08	7.65 ± 0.02	6.84 ± 0.03	7.24 ± 0.02	1.96 ± 0.12
I	III	−0.7 ± 0.6	4.70 ± 0.01	2.88 ± 0.04	4.80 ± 0.01	4.69 ± 0.01	4.67 ± 0.01	1.74 ± 0.04

The first digit is the average value, and the +/− sign is followed by the standard deviation (M ± SD—mean and standard deviation).

Table 3. Horizontal and vertical coordinate deviations of points A, N, and B measured three times by 29 doctors (n = 87) on 9 cephalograms, and 95% confidence intervals of the ANB angle.

Patient	ΔA_x (cm)	ΔA_y (cm)	$\Delta A_y/\Delta A_x$	ΔN_x (cm)	ΔN_y (cm)	$\Delta N_y/N_x$	ΔB_x (cm)	ΔB_y (cm)	$\Delta B_y/\Delta B_x$	ANB (°) [95% CI]
A	0.06	0.22	3.4	0.06	0.17	2.6	0.04	0.14	3.4	[2.1; 2.3]
B	0.11	0.17	1.5	0.07	0.06	0.8	0.17	0.57	3.4	[5.6; 6.0]
C	0.06	0.24	3.8	0.37	0.45	1.2	0.04	0.19	4.2	[−0.4; −0.2]
D	0.19	0.38	2.0	0.08	0.18	2.2	0.07	0.36	5.3	[4.4; 5.1]
E	0.07	0.20	3.0	0.08	0.15	1.8	0.03	0.20	6.5	[1.1; 1.3]
F	0.10	0.24	2.4	0.05	0.07	1.3	0.06	0.20	3.4	[7.6; 8.0]
G	0.05	0.18	3.4	0.09	0.34	3.7	0.12	0.59	4.8	[5.4; 5.8]
H	0.20	0.46	2.3	0.10	0.22	2.2	0.21	1.09	5.2	[−2.3; −2.0]
I	0.08	0.20	2.6	0.08	0.05	0.6	0.04	0.20	4.6	[−0.9; −0.7]
All	0.10	0.25	2.7	0.11	0.19	1.8	0.09	0.31	4.5	[−0.7; 5.3]

$\Delta A_x = A_x^{max} - A_x^{min}$; $\Delta A_y = A_y^{max} - A_y^{min}$; $\Delta N_x = N_x^{max} - N_x^{min}$; $\Delta N_y = N_y^{max} - N_y^{min}$; $\Delta B_x = B_x^{max} - B_x^{min}$; $\Delta B_y = B_y^{max} - B_y^{min}$.

The maximum ANB angle is described by coordinates such as A_x^{max}, A_y^{max}, N_x^{avg}, N_y^{min}, B_x^{min}, and B_y^{max}, while the minimum angle is described by coordinates such as A_x^{min}, A_y^{min}, N_x^{avg}, N_y^{max}, B_x^{max}, and B_y^{min}.

The significance of the relationship between the coordinates of points A, N, and B and the ANB angle was confirmed by the values of the Pearson correlation coefficients. The most significant correlation was for the A_x (six patients) and A_y (five patients) coordinates (Table 4).

Table 4. Correlation coefficients between coordinates of points A, N, and B and the ANB angle (n = 87).

Patient	Class	ANB (°)	Point A		Point N		Point B	
			A_X	A_Y	N_X	N_Y	B_X	B_Y
A	I	2.2 ± 0.4	0.295 *	−0.267 *	−0.410 **	−0.081	−0.223 *	0.104
B	II	5.7 ± 1.0	0.394 **	−0.137	0.312 *	0.061	−0.273 *	−0.207
C	III	0.2 ± 1.9	0.117	0.026	−0.013	0.088	0.134	−0.227 *
D	I	4.7 ± 1.1	0.672 ***	−0.538 ***	0.073	−0.274 *	0.070	−0.212 *
E	I	1.3 ± 1.0	0.524 ***	−0.322 *	0.037	−0.237 *	0.096	−0.154
F	II	7.1 ± 2.4	−0.014	−0.194	−0.295 *	0.039	0.119	0.313 *
G	II	5.3 ± 1.5	−0.186	0.127	−0.072	−0.018	−0.312 *	0.014
H	III	−1.8 ± 1.6	0.241 *	−0.241 *	0.202	0.074	−0.012	−0.195
I	III	−0.7 ± 0.6	0.350 *	−0.340 *	−0.085	−0.115	0.124	0.048

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The strong relationship between the ANB angle and the A_x variable was also confirmed by the results of the multiple regression analysis (Table 5).

The study participants, consisting of 29 orthodontists, analyzed nine cephalograms in triplicate. The results from the first and third measurements (taken one week apart) were used to assess repeatability. Errors were calculated using Dahlberg's formula, and interclass and intraclass correlation coefficients (ICCs) were determined. The Dahlberg error ranged from 0.265 to 0.665 (Table 6), while the ICC results ranged from 0.841 to 1.000, indicating a very high correlation between the measurements conducted by the 29 orthodontists (Table 7).

Table 5. The results of multiple regression analysis for the ANB angle—model parameter estimates.

Patient	Class	Constant	Point A		Point N		Point B	
			A_x (cm)	A_y (cm)	N_x (cm)	N_y (cm)	B_x (cm)	B_y (cm)
A	I	72.5	13.44	-	−14.31	-	-	-
B	II	-	20.19	-	-	-	−13.72	-
C	III	-	13.53	-	-	-	-	-
D	I	-	17.12	-	-	-	−13.02	-
E	I	−179.7	38.56	-	-	−9.83	-	-
F	II	-	7.66	-	−81.68	-	-	-
G	II	349.51	-	-	-	-	−32.79	-
H	III	-	11.38	-	-	-	-	-
I	III	-	16.64	-	-	-	-	-

Table 6. Dahlberg error and error ratio for ANB angle (°).

Patient	Class		ANB	Point A		Point N		Point B	
				A_X	A_Y	N_X	N_Y	B_X	B_Y
A	I	Dahlberg error	0.286	0.008	0.016	0.009	0.020	0.004	0.021
		Error ratio	13.0%	0.1%	0.6%	0.1%	0.4%	0.1%	1.2%
B	II	Dahlberg error	0.330	0.010	0.027	0.007	0.006	0.008	0.039
		Error ratio	5.8%	0.2%	1.0%	0.1%	0.1%	0.2%	2.0%
C	III	Dahlberg error	0.345	0.009	0.023	0.040	0.059	0.006	0.038
		Error ratio	174.6%	0.2%	0.9%	0.8%	1.3%	0.1%	3.0%
D	I	Dahlberg error	0.665	0.024	0.036	0.009	0.016	0.010	0.040
		Error ratio	14.3%	0.3%	1.1%	0.2%	0.3%	0.2%	2.1%
E	I	Dahlberg error	0.265	0.008	0.022	0.011	0.016	0.006	0.029
		Error ratio	19.6%	0.1%	0.8%	0.2%	0.3%	0.1%	1.6%
F	II	Dahlberg error	0.371	0.011	0.016	0.007	0.008	0.007	0.024
		Error ratio	5.2%	0.2%	0.6%	0.2%	0.2%	0.2%	1.5%
G	II	Dahlberg error	0.338	0.007	0.020	0.008	0.061	0.004	0.029
		Error ratio	6.3%	0.1%	0.8%	0.1%	1.5%	0.1%	1.9%
H	III	Dahlberg error	0.435	0.023	0.040	0.012	0.016	0.025	0.123
		Error ratio	24.4%	0.3%	1.0%	0.2%	0.2%	0.3%	6.3%
I	III	Dahlberg error	0.291	0.007	0.018	0.008	0.008	0.007	0.032
		Error ratio	39.6%	0.1%	0.6%	0.2%	0.2%	0.2%	1.8%

Table 7. Intraclass correlation coefficient (ICC) values for the ANB.

	ANB (°)	A_x (cm)	A_y (cm)	N_x (cm)	N_y (cm)	B_x (cm)	B_y (cm)
ICC	0.841	0.999	0.985	1.000	0.997	1.000	0.962

The ICC is used for determining whether the results of cephalometric measurements can be assessed in a reliable way by different orthodontists.

ICC values were interpreted according to Koo and Li [10] as follows:

- <0.50: Poor reliability of assessors;
- 0.5–0.75: Moderate reliability of assessors;
- 0.75–0.9: Good reliability of assessors;
- >0.9: Excellent reliability of assessors.

Consequently, an ICC of 0.782 for the ANB angle indicates that the reliability of the 29 assessing orthodontists can be considered "good".

The method employed to assess the repeatability and reproducibility of ANB angle measurements is outlined in Table 8. The variability (variance) of the coordinates of the designated points was categorized into three groups:

- Variability in the position of cephalometric points among the group of nine studied patients (between-group variance);
- Variability in the position of cephalometric points made by the 29 different doctors (reproducibility);
- Measurement errors across three measurements made by the same doctor on the same patients (repeatability).

Table 8. Results of the analysis of repeatability and reproducibility for the ANB angle measurement (°). R&R—Repeatability and Reproducibility).

Source of Variance	Estimated Sigma	Estimated Variance	R&R (%)	Total (%)
Repeatability (3 repetitions of measurements)	0.3733	0.1393	63.72	1.61
Reproducibility (29 orthodontists)	0.2816	0.0793	36.28	0.92
Patient (9 cephalograms)	2.9001	8.4108		97.47
Total R&R	0.4676	0.2187	100.00	2.53
Total	2.9376	8.6294		100.0

In the ideal scenario, almost all of the variability in measurement results should be attributed to between-group variance (individual patient variability), with only a negligible portion of variability arising from incomplete reproducibility among orthodontists and incomplete repeatability of measurements. The R & R (Repeatability and Reproducibility) module of STATISTICA v.13.3 (TIBCO Software Inc., Palo Alto, CA, USA) was employed to analyze repeatability and reproducibility.

The results for the ANB angle are presented in Table 8. In the last column, values indicating the relative contributions of variability from different sources are provided: repeatability accounts for 1.61%, reproducibility (among different doctors) accounts for 0.92%, interpatient variability accounts for 97.47%, and combined repeatability and reproducibility (R&R) accounts for 2.53%. In conclusion, the vast majority of the variability in the ANB angle is attributed to individual patient differences (cephalograms). This is a positive outcome that supports a favorable evaluation of the ANB angle measurement method. The total R&R result for ANB is 2.53%, well below 10%, signifying satisfactory quality (the highest acceptable R&R value being 15%).

3.2. Tau *Angle*

The Tau angle is a parameter used to determine the true bony sagittal maxillomandibular relationship (Figure 1). The Tau angle is constructed by identifying three cephalometric landmarks: Point T, which is the uppermost point at the junction of the frontal wall of the pituitary fossa and the tuberculum sellae; Point M, a constructed point representing the center of the largest circle that touches the frontal, upper, and palatal surfaces of the maxilla; and Point G, the focal point of the largest circle that touches the inner frontal, posterior, and lower edge of the mandibular symphysis. The Tau angle is formed between the two lines connecting points T and G and points M and G. The objective of the current study was to establish the mean and standard deviation of the Tau angle for three skeletal malocclusions. A Tau angle between 28° and 34° suggests a skeletal Class I malocclusion, while values below 28° indicate a Class III skeletal pattern, and values above 34° suggest a skeletal Class II pattern.

The Tau angle is determined by the coordinates of points T, G, and M and can be calculated according to the following relationship:

$$\text{Tau} = \text{arc tg}[(G_y - T_y)/(G_x - T_x) - (G_y - M_y)/(G_x - M_x)]/[1 + (G_y - T_y)/(G_x - T_x) * (G_y - M_y)/(G_x - M_x)]$$

The accuracy of Tau angle measurement relies on the precise positioning of the three points T, G, and M on the cephalograms. Table 9 displays the mean values of 87 Tau angle measurements, along with the coordinates of points T, G, and M. The dispersion of point G is vertical (with greater variability in the direction of the vertical axis, Δgy/ΔGx > 1), while the dispersions of points T and M are horizontal (Δty/ΔTx and Δmy/ΔMx < 1). The accuracy of Tau angle measurement is most significantly affected by the horizontal positioning accuracy of point M (Mx coordinate) and point T (Tx) (Table 10).

Table 9. Mean and standard deviation values of the Tau angle and coordinates of points T, G, and M measured on 9 cephalograms three times by 29 doctors (n = 87).

Patient	Class	Tau (°)	Point T		Point G		Point M	
			T_x (cm)	T_y (cm)	G_x (cm)	G_y (cm)	M_x (cm)	M_y (cm)
A	I	33.0 ± 1.5	3.85 ± 0.05	4.38 ± 0.03	5.76 ± 0.02	1.25 ± 0.03	5.81 ± 0.03	2.79 ± 0.02
B	II	40.4 ± 2.2	2.66 ± 0.01	4.46 ± 0.01	4.18 ± 0.02	1.61 ± 0.03	4.47 ± 0.04	2.89 ± 0.03
C	III	27.7 ± 4.2	2.85 ± 0.04	4.29 ± 0.03	4.93 ± 0.02	0.74 ± 0.04	4.82 ± 0.04	2.52 ± 0.03
D	I	33.1 ± 2.5	3.06 ± 0.05	4.80 ± 0.03	4.92 ± 0.02	1.50 ± 0.03	5.03 ± 0.05	3.35 ± 0.04
E	I	34.3 ± 2.0	3.55 ± 0.07	4.53 ± 0.03	5.70 ± 0.02	1.31 ± 0.04	5.71 ± 0.03	2.89 ± 0.02
F	II	38.6 ± 3.5	2.25 ± 0.05	4.41 ± 0.03	3.75 ± 0.02	1.21 ± 0.05	4.17 ± 0.04	2.82 ± 0.02
G	II	37.6 ± 2.7	3.89 ± 0.08	4.25 ± 0.03	5.44 ± 0.02	1.11 ± 0.03	5.72 ± 0.03	2.44 ± 0.03
H	III	25.8 ± 2.5	4.37 ± 0.05	6.71 ± 0.03	6.99 ± 0.02	1.27 ± 0.06	6.98 ± 0.07	3.95 ± 0.07
I	III	26.2 ± 2.2	2.79 ± 0.04	4.67 ± 0.03	4.58 ± 0.03	1.28 ± 0.04	4.52 ± 0.03	2.91 ± 0.03

The first digit is the average value, and the +/− sign is followed by the standard deviation (M ± SD—mean and standard deviation).

Table 10. Horizontal and vertical coordinate deviations of points T, G, and M measured three times by 29 doctors (n = 87) on 9 cephalograms, and 95% confidence intervals of the Tau angle.

Patient	ΔT_x (cm)	ΔT_y (cm)	$\Delta T_y/\Delta T_x$	ΔG_x (cm)	ΔG_y (cm)	$\Delta G_y/G_x$	ΔM_x (cm)	ΔM_y (cm)	$\Delta M_y/\Delta M_x$	Tau (°) [95% CI]
A	0.18	0.12	0.7	0.11	0.18	1.6	0.19	0.16	0.9	[32.5; 33.4]
B	0.09	0.08	0.9	0.10	0.19	1.9	0.23	0.19	0.8	[40.2; 41.4]
C	0.18	0.16	0.9	0.12	0.17	1.4	0.20	0.17	0.8	[26.3; 27.0]
D	0.17	0.15	0.9	0.09	0.18	2.0	0.34	0.23	0.7	[32.1; 33.3]
E	0.21	0.15	0.7	0.11	0.22	2.0	0.18	0.14	0.8	[33.9; 34.7]
F	0.20	0.11	0.5	0.13	0.24	1.9	0.20	0.13	0.6	[38.9; 40.2]
G	0.29	0.16	0.6	0.10	0.17	1.7	0.24	0.24	1.0	[37.4; 38.8]
H	0.23	0.17	0.7	0.09	0.35	3.7	0.33	0.37	1.1	[25.0; 25.9]
I	0.14	0.10	0.8	0.16	0.16	1.0	0.22	0.24	1.1	[25.5; 26.3]
All	0.19	0.13	0.7	0.11	0.21	1.9	0.24	0.21	0.9	[24.0; 40.4]

$\Delta T_x = T_x^{max} - T_x^{min}$; $\Delta T_y = T_y^{max} - T_y^{min}$; $\Delta G_x = G_x^{max} - G_x^{min}$; $\Delta G_y = G_y^{max} - G_y^{min}$; $\Delta M_x = M_x^{max} - M_x^{min}$; $\Delta M_y = M_y^{max} - M_y^{min}$.

The significance of the relationship between the coordinates of points T, G, and M and the Tau angle was confirmed by the values of the Pearson correlation coefficients (Table 11). The most significant correlation was for the T_x and M_x coordinates (six patients).

Table 11. Correlation coefficients between coordinates of points T, G, and M and the Tau angle (n = 87).

Patient	Class	Tau (°)	Point T		Point G		Point M	
			T_X	T_Y	G_X	G_Y	M_X	M_Y
A	I		−0.595 ***	−0.584 *	0.085	−0.247 *	0.444 ***	0.127
B	II		−0.216 *	−0.036	0.059	0.018	0.371 ***	0.139
C	III		−0.051	−0.083	−0.077	0.020	0.211	0.195
D	I		0.055	−0.148	−0.136	0.013	0.262 *	−0.075
E	I		−0.308 **	−0.220 *	−0.055	−0.086	0.270 *	0.306 **
F	II		−0.324 **	−0.234 *	0.151	0.355 **	−0.114	−0.011
G	II		−0.426 ***	−0.034	−0.092	0.282 **	−0.109	−0.068
H	III		−0.056	−0.120	−0.037	0.045	0.211 *	0.078
I	III		−0.228 *	−0.221 *	−0.375 ***	0.290 **	0.430 ***	−0.320 **

* $p < 0.05$, ** $p < 0.001$, *** $p < 0.001$.

The strong relationship between the ANB angle and the A_x variable was also confirmed by the results of the multiple regression analysis (Table 12).

Table 12. The multiple regression analysis results for the Tau angle—model parameter estimates.

Patient	Class	Constant	Point T		Point G		Point M	
			T_X (cm)	T_Y (cm)	G_X (cm)	G_Y (cm)	M_X (cm)	M_Y (cm)
A	I	−18.6	−16.48	-	-	-	19.81	-
B	II	−98.7	−37.73	-	-	-	20.67	-
C	III	2.7	-	-	-	-	26.85	-
D	I	115.1	-	-	-	-	12.47	-
E	I	−10.88	-	-	-	-	26.11	-
F	II	56.97	−21.23	-	-	-	24.38	-
G	II	67.3	−14.78	-	-	24.91	-	-
H	III	−25.6	-	-	-	-	7.37	-
I	III	24.8	-	-	−32.00	-	32.67	-

The measurement errors for the angle Tau and the coordinates of points T, B, and M were estimated according to the Dahlberg formula and the ICCs. The Dahlberg error ranged from 0.891 to 1.639 (Table 13), while the results for ICC ranged from 0.147 to 0.624, which indicates a weak correlation between the measurements made by the 29 orthodontists (Table 14).

The results of the analysis of repeatability and reproducibility for the Tau angle are presented in Table 15. The repeatability of the results accounts for 4.30% of the total variability, reproducibility (among different doctors) accounts for 3.94%, interpatient variability accounts for 91.76%, and combined repeatability and reproducibility (R&R) accounts for 8.24%. Consequently, the vast majority of the variability in the Tau angle can be attributed to individual patient differences (cephalograms). This is a positive outcome that supports a favorable evaluation of the Tau angle measurement method. The total R&R result for Tau is 8.24%, which falls below 10%, indicating satisfactory quality.

3.3. *ANB vs. Tau*

The orthodontists involved in the study demonstrated significantly greater accuracy in measuring the ANB angle compared to the Tau angle. The Dahlberg error for Tau angle measurements was approximately three times larger than that for the ANB angle. Similarly, the ICC for the Tau angle was more than three and a half times smaller than that for the ANB angle. Furthermore, the R&R error for Tau angle measurements was more than three times larger compared to that for ANB angle measurements (Table 16). In summary, the results indicate that the ANB angle measurements exhibit less error compared to the Tau angle measurements. This discrepancy is influenced by the smaller dispersion of horizontal coordinates of the points that have the greatest impact on angle measurement error.

Table 13. Dahlberg error and error ratio (P).

Patient	Class		Tau	Point T		Point G		Point M	
				T_X	T_Y	G_X	G_Y	M_X	M_Y
A	I	Dahlberg error Error ratio	0.891 2.7%	0.033 0.9%	0.023 0.5%	0.015 0.3%	0.017 1.4%	0.020 0.3%	0.021 0.7%
B	II	Dahlberg error Error ratio	1.348 3.3%	0.012 0.4%	0.008 0.2%	0.017 0.4%	0.017 1.1%	0.028 0.6%	0.027 0.9%
C	III	Dahlberg error Error ratio	1.015 3.7%	0.012 0.4%	0.011 0.2%	0.023 0.5%	0.027 3.6%	0.017 0.4%	0.020 0.8%
D	I	Dahlberg error Error ratio	1.197 3.6%	0.036 1.2%	0.024 0.5%	0.013 0.3%	0.020 1.3%	0.026 0.5%	0.028 0.8%
E	I	Dahlberg error Error ratio	0.954 2.8%	0.039 1.1%	0.019 0.4%	0.019 0.3%	0.024 1.9%	0.010 0.2%	0.009 0.3%
F	II	Dahlberg error Error ratio	1.170 3.0%	0.023 1.0%	0.015 0.3%	0.017 0.5%	0.033 2.8%	0.019 0.4%	0.017 0.6%
G	II	Dahlberg error Error ratio	1.407 3.7%	0.038 1.0%	0.013 0.3%	0.012 0.2%	0.019 1.7%	0.019 0.3%	0.029 1.2%
H	III	Dahlberg error Error ratio	1.639 6.4%	0.022 0.5%	0.016 0.2%	0.011 0.2%	0.033 2.7%	0.048 0.7%	0.050 1.3%
I	III	Dahlberg error Error ratio	1.228 4.7%	0.016 0.4%	0.013 0.3%	0.018 0.4%	0.022 1.7%	0.023 0.5%	0.026 0.9%

Table 14. Intraclass correlation coefficient (ICC) values.

	Tau (°)	T_X (cm)	T_Y (cm)	G_X (cm)	G_Y (cm)	M_X (cm)	M_Y (cm)
ICC	0.147	0.586	0.517	0.364	0.624	0.562	0.376

Table 15. Results of the analysis of repeatability and reproducibility for the Tau angle measurement (°). R&R- Repeatability and Reproducibility).

Source of Variance	Estimated Sigma	Estimated Variance	R&R (%)	Total (%)
Repeatability (3 repetitions of measurements)	1.0273	1.0552	52.21	4.30
Reproducibility (29 orthodontists)	0.9828	0.9658	47.79	3.94
Patient (9 cephalograms)	4.7457	22.5214		91.76
Total R&R	1.4216	2.0211	100.00	8.24
Total	4.9540	24.5425		100.00

Table 16. Comparison between the Dahlberg error, intraclass correlation coefficient (ICC), and repeatability and reproducibility (R&R) of ANB and Tau measurements made by 29 orthodontists, as well as mean coordinate deviations of points that most strongly affect angle measurements.

Angle	Dahlberg Error	ICC	Total R&R	DCA (cm)
ANB	0.265–0.665	0.841–1.000	2.53%	$\Delta A_x = 0.10$
Tau	0.891–1.639	0.147–0.624	8.24%	$\Delta M_x = 0.24$
Tau/ANB	2.91	0.27	3.26	2.40

DCA—the average deviation of the coordinate that determines the accuracy of the angle measurement.

The ability to accurately classify patients into one of the three skeletal classes based on the measured ANB and Tau angles is similar ($p < 0.001$). The Cohen's kappa value based on the ANB angle values and the gold standard is 0.778, which is slightly higher (indicating better agreement) than that based on the Tau angle values (0.722). Cohen's kappa is a reliability coefficient used to measure the consistency between two methods measuring the same variable, which is nominal and dependent. Cohen's kappa values range from −1 to 1, with values closer to 1 indicating greater agreement between the two methods (Table 17).

Table 17. The Cohen's kappa values based on the ANB compared to the Tau angle.

(a)

ANB (°)	Class: I n = 261	Class: II n = 261	Class: III n = 261	Chi-squared test
0°–4° (n = 224)	193 (73.9%) [A]	6 (2.3%)	25 (9.6%)	$\chi^2 = 988.2$ df = 4 $p < 0.001$ (A vs. BC)
>4° (n = 324)	66 (25.3%)	248 (95.0%) [B]	10 (3.8%)	
<0° (n = 235)	2 (0.8%)	7 (2.7%)	226 (86.6%) [C]	

(b)

Tau (°)	Class: I n = 261	Class: II n = 261	Class: III n = 261	Chi-squared test
28°–34° (n = 209)	169 (64.7%) [A]	9 (3.4%)	31 (11.9%)	$\chi^2 = 890.1$ df = 4 $p < 0.001$ (A vs. BC)
>34° (n = 347)	90 (34.5%)	248 (95.0%) [B]	9 (3.4%)	
<28° (n = 227)	2 (0.8%)	4 (1.5%)	221 (84.7%) [C]	

(c)

Tau (°)	ANB (°): 0°–4° n = 224	ANB (°): > 4° n = 324	ANB (°): < 0° n = 235	Chi-squared test
28°–34° (n = 209)	130 (58.0%) [A]	50 (15.4%)	29 (12.3%)	$\chi^2 = 748.2$ df = 4 $p < 0.001$ (A vs. BC)
>34° (n = 347)	73 (32.6%)	274 (84.6%) [B]	0 (0.0%)	
<28° (n = 227)	21 (9.4%)	0 (0.0%)	206 (87.7%) [C]	

(A) Kappa = 0.778 [0.741; 0.815], SE = 0.036, N = 783; (B) Kappa = 0.722 [0.682; 0.763], SE = 0.036, N = 783; (C) Kappa = 0.662 [0.618; 0.706], SE = 0.036, N = 783.

4. Discussion

Cephalometric assessment of sagittal discrepancy plays a crucial role in orthodontic evaluation, facilitating the development of appropriate treatment plans [11,12]. Over time, numerous researchers have sought to identify the most stable and reproducible anthropometric points, regardless of the growth direction or orthodontic treatment provided. However, it is important to note that no method is entirely free of errors, and in certain situations, the obtained results may need validation through an alternative method [12]. Most studies focusing on cephalometric analysis typically concentrate on a single ethnic group. However, the diverse set of characteristic features observed in cephalometric analyses for patients from specific ethnic groups or populations residing in different regions necessitates a comprehensive comparative evaluation of individual indicators. This is crucial for accurately assessing the relationships between maxillary bases, alveolar processes, and teeth in both sagittal and vertical dimensions [13]. Given the recent introduction of a new parameter for assessing sagittal discrepancy—Tau angle analysis [3], which its authors claimed to be more reliable compared to ANB analysis—we aimed to conduct a comparative evaluation of both ANB angle analysis and Tau angle analysis in terms of assessing sagittal discrepancy.

We also assessed the stability of identifying anthropometric points associated with each of these angles in relation to discrepancies between horizontal and vertical axes. Additionally, we conducted an analysis of the repeatability and reproducibility (R&R) of measurements, comparing the variability in landmark identification by the same observer and different observers in the same study. Furthermore, we evaluated the accuracy of classifying patients into one of three skeletal classes by analyzing both ANB and Tau angle values. Recent research has demonstrated the potential of employing artificial intelligence for precise and consistent analysis, even in 3D images. The outcomes of testing deep learning techniques based on Convolutional Neural Networks (CNNs) have shown them to be effective and accurate, comparable to the expertise of an experienced observer while being significantly faster. These findings suggest the feasibility of utilizing AI in orthodontic diagnostics, which holds substantial clinical importance in terms of result consistency and rapidity of analysis. It is worth noting, though, that the application of this technology to 3D images has limitations due to patient radiological protection considerations and should be reserved for the most complex cases. For simpler cases analyzed in 2D projection, this approach can be readily implemented [14,15].

Studies conducted by Maheen Ahmed, Attiya Shaikh, Mubassar, and Fida [11] regarding various cephalometric analyses have consistently shown that the ANB angle is the most precise and reliable indicator for evaluating the maxillomandibular relationship in the sagittal plane. The findings of our study support this conclusion as well. The ANB angle measurements exhibited smaller errors compared to the Tau angle measurements, primarily due to the narrower dispersion of horizontal coordinates of the points that have the greatest impact on angle measurement errors. The results for ANB measurements, including repeatability (1.61%), reproducibility (0.92% between different observers), interpatient variability (97.47%), and combined reproducibility and repeatability (2.53%), underscore the ANB angle's dependency on individual variability. This emphasizes the ANB angle's effectiveness as a standard parameter for evaluating sagittal relationships. The reliability of our data was further enhanced by the double-blinding of the study sample, where observers were unaware of both the clinical parameters of patients and the purpose of the analyses, ensuring unbiased evaluation.

Regarding errors associated with the identification of anthropometric points [10,12,16–22], the majority of studies that have evaluated the reproducibility and reliability [1,3,10,12,20–26] of individual landmarks have reported errors in point identification. Accurate assessment and repeatability are particularly crucial in growing patients, especially when dealing with the imprecise determination of points A, N, and B. These points can undergo significant positional changes during growth and orthodontic treatment, making it challenging to accurately assess the sagittal discrepancy between the jaws [25]. The reliability of anthropometric point determination is a critically important factor that underpins the repeatability of both linear and angular measurements [1,3,10,12,20–23]. When the identification of points cannot be consistently and reliably reproduced, the overall measurement used in cephalometric analysis becomes susceptible to significant errors that can impact diagnosis and treatment planning. In the sagittal analysis of the ANB angle, the precise evaluation of points A and B in relation to the x-axis, as well as the evaluation of point N in relation to the y-axis, holds particular significance [12]. Similarly, in the assessment of the Tau angle, attention should be paid to the accurate evaluation of points T and M in relation to the x-axis and point G in relation to the y-axis. The findings from our study suggest that the discrepancy along the horizontal axis (x-axis) when determining points A and B is minimal, potentially indicating a high level of accuracy in influencing ANB angle measurements. In a study by Durao [24], the ICC for the x-component at point B was less than 0.9, and for the y-axis at point N, it was also less than 0.9. However, the ICC values consistently ranged between 0.75 and 0.9, which was considered good. The assessment of the vertical divergence of point N, which is significantly higher compared to that of its horizontal component, aligns with this observation. Moreover, the intragroup correlation coefficients demonstrate high consistency in point identification, indicating the measurement's high reliability when assessed by different observers. Similar results were obtained in the study conducted by Durao et al. [24].

The introduction of a new cephalometric measurement has the potential to significantly reduce errors in ANB measurement, particularly in growing patients who frequently undergo changes in the positions of points A, N, and B. Nevertheless, the adoption of this new measurement should also be approached with a degree of caution and careful consideration. Contrary to the claims made by Gupta P. et al. [3], it is evident from the present study that points M and G, while located near the central positions in the maxilla and mandibular symphysis, are not less susceptible to change compared to other points, including A and B. Furthermore, there is no clear evidence to support the assertion that the Tau angle is immune to mandibular rotation or consistently yields stable results for determining the correct direction of sagittal defects. The study also highlights that errors related to anthropometric point identification are more significant than errors in repeatability or reproducibility of landmarks in both ANB and Tau angle assessments. In terms of the ability to accurately classify patients into one of the three skeletal classes based on ANB and Tau angle measurements, the assessment remains similar, with the ANB angle continuing to serve as the gold standard.

The primary limitations of this study were the number of patients and its cross-sectional nature, accompanied by associated limitations. Other constraints encompassed alterations in the position of anthropometric points A, N, and B, and the potential for changes in points G and M due to the patients' growth during puberty. Additionally, the accuracy of determining the T point presented a limitation. Consequently, further research is warranted, particularly randomized controlled trials (RCTs) comparing alternative methods for evaluating sagittal discrepancies in adequately large groups.

5. Conclusions

This study demonstrated significantly greater accuracy in measuring the ANB angle compared to the Tau angle. The Dahlberg error associated with the measurement of the Tau angle was approximately three times larger than that of the ANB angle. Furthermore, the intraclass correlation coefficient for the Tau angle was more than three and a half times smaller than that for the ANB angle. Similarly, the R&R error for the Tau angle measurement exceeded that for the ANB angle by more than threefold. In conclusion, the measurement results for the ANB angle exhibit lower levels of error when compared to the results for the Tau angle. Despite the introduction of new measurements based on novel landmarks, ANB angle analysis, considered the gold standard in assessing sagittal maxillomandibular relationships, remains a fundamental indicator for determining the sagittal direction of malocclusions.

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8.3. Publikacja 3

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Systematic Review

Methods of Anterior Torque Control during Retraction: A Systematic Review

Anna Ewa Kuc [1], Jacek Kotula [2,*], Marek Nahajowski [3], Maciej Warnecki [4], Joanna Lis [2], Ellie Amm [5], Beata Kawala [2] and Michał Sarul [3]

1. Dental Star Specjalistyczne Centrum Stomatologii Estetycznej, 15-215 Białystok, Poland; dental.star@wp.pl
2. Department of Dentofacial Orthopedics and Orthodontics, Wroclaw Medical University, Krakowska 26, 50-425 Wroclaw, Poland; joanna.lis@umw.edu.pl (J.L.); beata.kawala@umw.edu.pl (B.K.)
3. Department of Integrated Dentistry, Wroclaw Medical University, Krakowska 26, 50-425 Wroclaw, Poland; marek_nahajowski@wp.pl (M.N.); michal.sarul@umw.edu.pl (M.S.)
4. Private Practice, Prasi-Dent, Niemodlinskiej 63, 45-864 Opole, Poland; maciej.warnecki@gmail.com
5. Department of Orthodontics and Dentofacial Orthopedics, Boston University, Boston, MA 02118, USA; ellieamm@hotmail.com

* Correspondence: j_kotula@poczta.onet.pl

Abstract: Background: There are various methods of controlling the inclination of the incisors during retraction, but there is no evidence as to the advantages of some methods over others. The purpose of this systematic review and meta-analysis was to determine the effectiveness of the methods used to control torque during anterior teeth retraction. Methods: In accordance with the PRISMA guidelines, the main research question was defined in the PICO format [P: patients with complete permanent dentition; I: the maxillary incisor torque after (I) and before I retraction with straight-wire appliance and different modes of torque control; O: statistically significant differences in torque values of the upper incisors after orthodontic treatment]. The MEDLINE, EMBASE, and Cochrane Central Register of Controlled Trials databases were searched for keywords combining: retraction orthodontics, torque control orthodontics, torque orthodontics, inclination orthodontics, torque control retraction. The articles were subjected to risk of bias and quality analyses with the ROBINS-I protocol and the modified Newcastle–Ottawa QAS, respectively. Meta-analyses were performed with both fixed- and random-effects models. Results: 13 articles were selected in which total number of 580 subjects took part. In all studies, incisors were retroclined during retraction by 2.46° (mean difference), which was statistically significant. Considering the articles separately, the differences in torque between the study group and the control group were statistically significant in six articles. The Q statistic was 36.25 with $p = 0.0003$ and $I^2 = 66.9\%$, which indicated a high level of study heterogeneity. Conclusion: Both properly performed corticotomy and en-masse retraction using orthodontic microimplants seem to be the most effective and scientifically validated methods of torque control. Further high-quality research is needed to perform better quality analyses and draw more reliable conclusions.

Keywords: tooth retraction; torque control; orthodontics

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1. Introduction

Torque control is a key element in the extraction of the first premolars during orthodontic treatment [1–16]. In such cases, it is necessary to thoroughly diagnose and plan the appropriate control of the torque. The authors tried to show which of these methods gives the greatest effectiveness [6–19].

During orthodontic treatment, torque control of the anterior teeth roots is relevant. It ensures the stability of the proper interincisal angle that, in turn, is responsible for the proper support of soft tissues [20–22], providing a harmonious facial profile [6,7]. The labio-palatal inclination of the long axis of the incisors is also relevant to maintaining a healthy periodontium, which minimises the risk of recurrence after treatment, recession, fenestration or dehiscence in the anterior part of the dental arch [6].

In addition to attempts to control the inclination of the incisors during their retraction directly related to the interaction of the orthodontic wire with the surface of the breech gap, a modification of the direction of the force vector can also be used. In particular, the use of orthodontic mini-implants—one of the greatest achievements of orthodontics of the last 20 years—should be taken into account here. This method can affect not only better anchor control but also the way the incisors move during their retraction [22].

There is a need for the mechanical control of the incisor root position in the treatment of moderate to severe crowding, bimaxillary protrusion [12], and open bite or Class II malocclusion. The extraction of premolars is often necessary to distalize canines into good position. Spaces occurring mesially to distalised canines make the incisors particularly susceptible to uncontrolled/excessive inclination. To avoid this effect, such different methods of incisor torque control were suggested as brackets with increased built-in torque [7], arch torsion [12], placement of temporary intraoral skeletal anchorage devices (TISAD) [8–11,14–17] that enable group distal movement of the "social six" (en-masse retraction) [8,12,13], and a mini-implant inserted between the maxillary incisors [9,14,15]. Regardless of various procedures that support proper root position during space closure, the evaluation of their effectiveness is based almost exclusively on individual clinicians' experience.

Therefore, this systematic review aims to objectively determine the effectiveness of different methods for root torque control of the maxillary incisors during their orthodontic retraction, and thus to identify which of the suggested procedures deserve the highest recommendations in clinical practice.

2. Methods

The systematic review was registered in the PROSPERO database under identification number CRD42021215408.

The study was conducted according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [3,4]. The research questions were defined in PICO format:

Population (P): The patients undergoing the study had complete permanent dentition.

Intervention (I): The orthodontic extraction treatment with braces using a straight arch technique and an additional method for incisor root torque control was used.

Comparison (C): Evaluation of the torque of the incisor roots before and after the treatment.

Outcome (O): The influence of methods of incisor root torque control on the final effect of orthodontic treatment.

The following electronic databases were searched by two researchers (AK, JK): PubMed, EMBASE, and Cochrane Central Register of Controlled Trials [20], entering the following keywords:

- incisor retraction & orthodontics
- incisor root torque control & orthodontics
- root torque & orthodontics
- incisor inclination & orthodontics
- incisor root torque control & retraction

Search filters include the time of publication of the article, the last 10 years, and publications that appeared in English in relation to conventional labial/buccal braces.

Based on the information provided in abstracts, articles were selected according to the following criteria: randomised clinical trials (RCTs) and controlled clinical prospective trials (CCTs). Individual case reports, case series reports, literature reviews, experimental studies, studies with limited data (including conference abstracts and journal writings), studies involving an unrepresentative group of patients (less than 10 patients), studies concerning patients with syndromes, and animal experiments were rejected. Articles unrelated to the subject of the planned study were also excluded.

In terms of the selected full-text articles, those that did not include information concerning the change in the inclination of the maxillary incisors after orthodontic treatment were excluded. Articles that did not report the number of patients who completed orthodontic treatment were also rejected.

For the remaining articles, references were reviewed, and such journals as *American Journal of Orthodontics, Dentofacial Orthopedics*, *International Orthodontics*, *Journal of Clinical Orthodontics*, and *Angle Orthodontist* were manually searched.

The following data were extracted from reviewed articles: year of publication, group size, characteristics of treatment and control groups, method of root torque control, maxillary incisor root torque before and after orthodontic treatment, together with mean changes in these angular values (Table 1).

Table 1. Data from articles.

Study	Control Group	Study Group	Age of Participants (yrs)	Treatment Strategy	Change in the [illegible] during the Observation Period	SD	Median Difference of [illegible] between Groups	SE (Standard Error)	p	Contribution to Analysis Result (%)
[illegible]										
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

3. Risk of Bias

The risk of bias analysis was performed for various articles using the Cochrane Collaboration's tool [2]. The following criteria were used: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of assessors, incomplete outcome data, reporting of selective outcomes and other potential sources of bias. A modified Newcastle-Ottawa Quality Assessment Scale [7] consisting of three parts was used for the qualitative assessment:

(1) patient selection, where the following elements were evaluated:
  (a) the representativeness of the group exposed to the test agent,
  (b) the selection of patients for a control group,
  (c) the source of data concerning individual patients,
  (d) a demonstration that studied effects did not occur at the beginning of the study.

A maximum of 1 point was awarded for each sub-point, resulting in a possible score of 4 points.

(2) Confounding factors that evaluated whether a control group was identical to a treatment group in terms of other factors that could possibly influence the outcomes.

In this category, 0–2 points were awarded according to the significance of the influence of confounding factors.

(3) Outcome assessment, which analysed:
  (a) the blinding of assessors,
  (b) the duration of observation,
  (c) the percentage of patients who completed the study.

Enabling a maximum score of 3 points.

4. Statistical Analysis

For each article, a statistical analysis was performed for the differences in the mean changes in maxillary incisor inclinations between treatment and control groups. Studies with a statistically significant difference were selected. The outcomes are shown graphically as a forest plot (blobbogram). Moreover, a heterogeneity analysis of the included studies was conducted. For this purpose, a heterogeneity test based on the Q-statistic was performed, and I^2 was calculated. All calculations were performed using Statistica 13 PLM software (StatSoft Poland, Krakow, Poland).

5. Results

By entering keywords into the included databases, 3175 abstracts were yielded. Forty-four articles were initially validated as eligible for the systematic review, and they were analysed in detail. A final total of 13 articles was selected, including 7 RCTs and 6 CCTs. The complete selection process is shown in Figure 1.

5.1. Group Size

The total number of participants was 580. The average group size was 20 patients. The largest groups were described by Chen et al. [2] and Xu et al. [8]: 32 patients per group. The smallest groups were reported by Deepak et al. [9]: 10 participants per group. In most studies, the sizes of the study and control groups were identical (Table 1).

5.2. Age and Sex

The ages of the patients varied significantly between articles, ranging from 10 years in [8] to 35 years in [7]. Therefore, some patients were treated before or during maximum growth, while others were treated upon reaching adulthood. The studies by Sadeki et al. [10], Lee et al. [11], Jiao et al. [12], and Jeea et al. [13] included only women. The studies conducted by Deepak et al. [9] and Ruan et al. [14] lacked information concerning patients' sex. In each of the remaining studies, the female group was larger than the male group (Table 1).

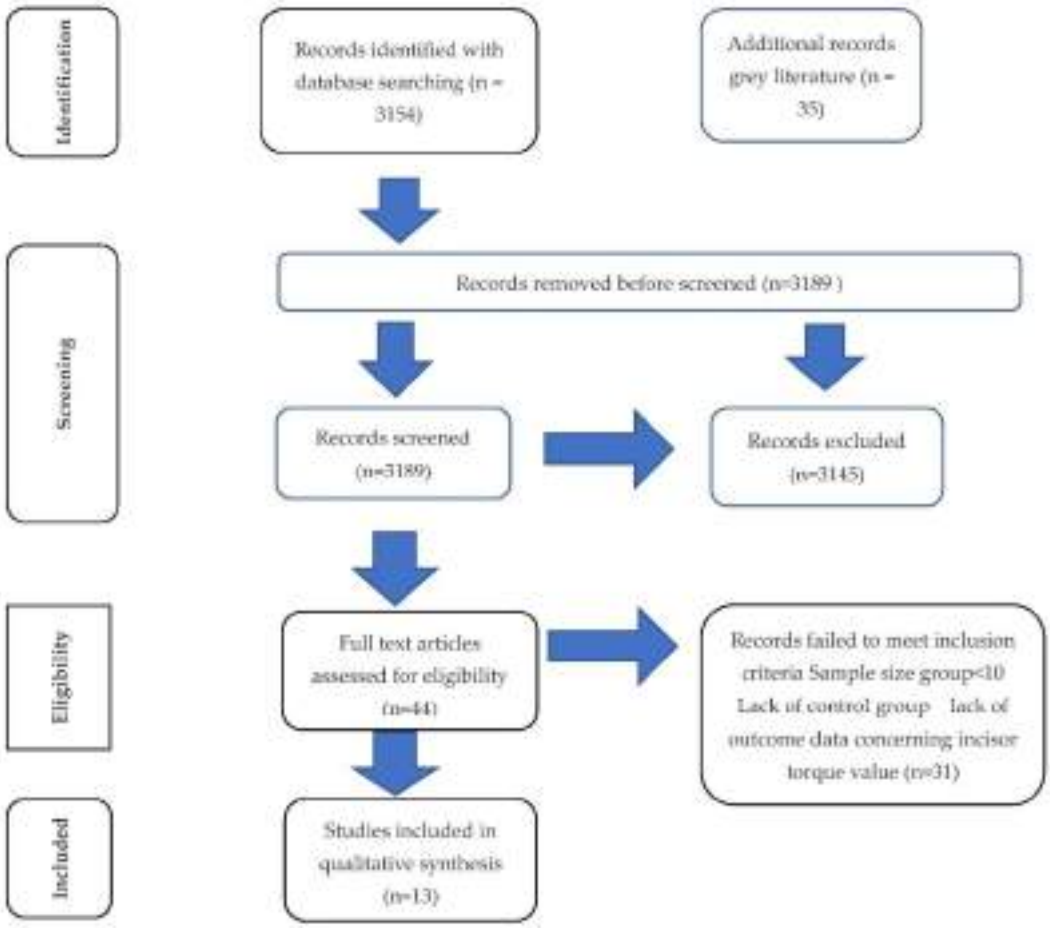

Figure 1. PRISMA flow diagram.

5.3. *Treatment Strategy*

In all treated patients, extractions of the maxillary premolars were performed to gain space for the incisor and canine retraction. In 10 articles, maximum anchorage was used as TISAD in the treatment groups [8–11,14–17]. Other studies evaluated the effects of changes in the width of the slot inclination in brackets placed on the first upper molars [7], the use of corticotomy [17,19], and the use of elastics and power chains [12]. Those studies also compared the effectiveness of en-masse retraction to two-step anterior teeth retraction [8].

5.4. *Risk Analysis*

The outcome assessment findings for the risk of bias in the randomised clinical trials and the qualitative analysis of CCTs are shown in Tables 2 and 3, respectively.

Table 2. Risk of bias assessment in the RCTs.

Study	Random Sequence Generation	Allocation Concealment	Blinding of Participants and Personnel	Blinding of an Outcome Assessment	Incomplete Outcome Data	Selective Reporting	Other Bias
Al-Sibaie and Hajeer (2013) [16]	Low	Low	High	Low	Low	Low	Low
Davoody et al. (2012) [15]	Low	Low	High	Unclear	Low	High	Low
Sadeka et al. (2019) [10]	Low	Low	High	High	Low	Low	Unclear
Al-Imam et al. (2019) [18]	Low	Low	High	Low	Low	Low	Low
Chen et al. (2020) [7]	Low	Low	High	Low	Low	Moderate	Unclear
Tunçer et al. (2017) [17]	Moderate	Low	High	Low	Low	Moderate	Low
Xu et al. (2010) [8]	Low	Low	High	Low	Low	Low	Unclear

Table 3. The quality assessment of CCTs according to the modified Newcastle-Ottawa Scale.

Study	Selection	Comparability	Outcome Assessment
Deepak et al. (2014) [9]	4	2	2
Lee and Kim (2011) [11]	4	2	2
Koyama et al. (2011) [19]	4	2	2
Ruan et al. (2018) [14]	3	–	1
Zhao et al. (2018) [12]	3	–	2
Jeez et al. (2013) [13]	3	–	2

5.5. *Main Parameter: Change in the Maxillary Incisor Root Torque*

In all studies, incisor inclination was observed during the retraction movement, i.e., there was a vestibular root torque. In the treatment groups, the mean change in buccal-palatal inclination of the incisor roots was 10.46°. The greatest change in incisor torque (19.13°) was described by Lee et al. [11], in the group where mini-implants were used. Completely different results were obtained by Sadeka et al. [10] who found the smallest change, 4.41°, in the root inclination of the anterior teeth in a vestibulo-palatal direction after mini-implants were used on the vestibular side to retract the anterior teeth (Table 1).

Taking into account all studies, the mean difference in the upper incisor inclination between the control and treatment groups was 2.46°, which was statistically significant ($p = 0.0003$). The largest discrepancy between groups was observed by Davoody et al. [15]. In contrast, no discrepancy was observed between groups by Deepak et al. [9] (Table 1).

5.6. *The Effectiveness of Methods for Upper Incisor Torque Control*

Out of 13 articles [6–19] included in this review, the differences between study and control groups in upper anterior teeth inclination were statistically significant ($p = 0.05$) in only 6 articles. The analysis results are shown in a forest plot (blobbogram) [20] (Figure 2).

The results of the studies and their significant statistical value are shown below, in gradation from the study with the highest to the lowest statistical significance (Table 4).

Table 4. The most efficient treatment strategies of anterior torque control during retraction.

Study	Treatment Strategy	Median Difference of U1-Inclination between Groups (G1–G2, °)	p	Contribution for Analysis Result (%)
Al-Imam et al. (2019) [18]	G1: 2-step retraction with corticotomy; G2: 2-step retraction without corticotomy	1.52	0.0109	13.78
Al-Sibaie and Hajeer (2013) [16]	G1: retraction with TADs; G2: 2-step retraction with TPA	2.91	0.0003	12.75

Table 4. *Cont.*

Study	Treatment Strategy	Median Difference of U1-Inclination between Groups (G1–G2, °)	*p*	Contribution for Analysis Result (%)
Sadeka et al. (2019) [10]	G1: retraction with TADs, buccal mechanics; G2: retraction with TADs, lingual mechanics	5.85	0	9.39
Chen et al. (2020) [2]	G1: retraction with PASS; G2: retraction with MBT	4.82	0.0061	7.69
Zhao et al. (2018) [12]	G1: retraction with elastics (TADs for anchorage control); G2: retraction with power chains (TADs for anchorage control)	7.14	0.0017	5.73
Davoody et al. (2012) [15]	G1: 2-step retraction; G2: retraction with TADs	8.02	0.0207	3.14

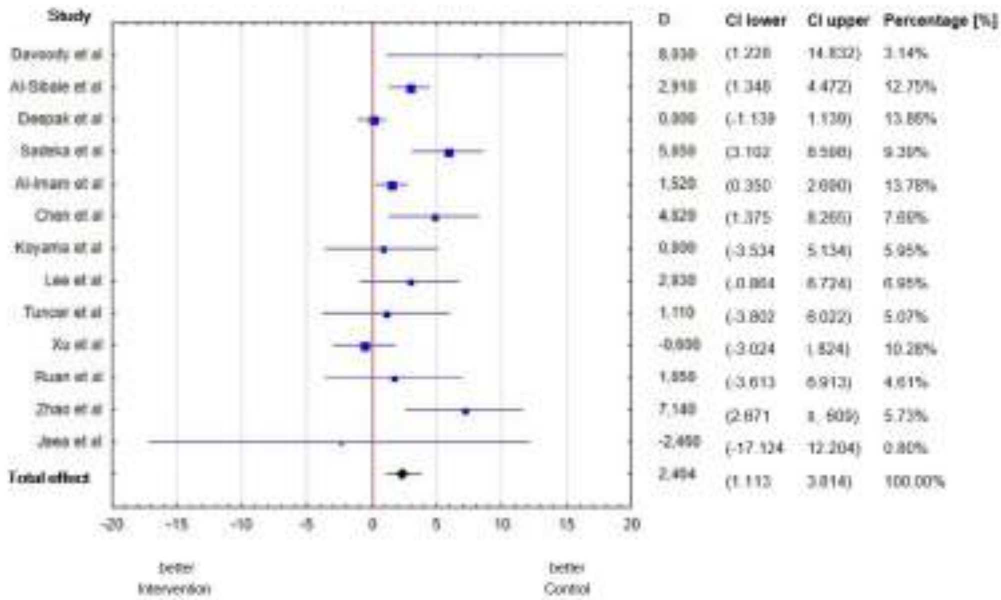

Figure 2. The mean differences in the incisor inclination between the treatment and control groups.

(1) Al-Imam et al. [18] revealed that corticotomy during incisor retraction reduces their inclination by an average of 1.5° compared with non-surgically assisted retraction.

(2) Al-Sibaie et al. [16] revealed that en-masse retraction of the anterior teeth using TISAD results in an incisor inclination on average 2.9° lower compared with the standard two-step process.

(3) Sadeka et al. [10] revealed that the en-masse retraction using mini-implants and arches on the vestibular side results in a reduction of maxillary incisor inclination by an average of 5.85° compared with the same en-masse movement from the lingual access and mini-implants placed on the palate.

(4) Chen et al. [2] revealed that patients treated with the PASS system had on average 4.8° lower maxillary incisor inclination compared with patients treated with the MBT system.
(5) Zhao et al. [12] found that the use of intramaxillary elastics during incisor retraction results in an inclination of the maxillary anterior teeth that is on average 7.14° lower compared with the use of power chains.
(6) Davoody et al. [15] found that the standard two-step retraction using an extra-intrusive arch results in a maxillary incisor inclination on average 8° lower compared with TISAD-assisted en-masse retraction.

Q was 36.25 with $p = 0.0003$ and $I^2 = 66.9\%$. Those data indicate a high level of study heterogeneity. This is most likely due to the different orthodontic techniques that were used in individual studies.

Additionally, an analysis of the heterogeneity of the studies included in the meta-analysis was performed. For this purpose, a test of heterogeneity based on Q and I^2 was performed. The results are summarized in Table 5.

Table 5. Heterogeneity analysis.

Q	df	p	I^2	Lower Limit 95% PU (I^2)	Upper Limit 95% PU (I^2)
36,249	12	0.0003	66.90%	40.72%	81.51%

As is shown, I^2 is 67%, which means that 67% of the differences observed between the test results are the result of heterogeneity. They are the result of differences between populations and the methods of torque control.

Table 6 shows the results of the heterogeneity of the studies broken down into the individual studies. The change in the cumulative effect shows how the result of meta-analysis would change if the study were not included. The percentage share of the study in the meta-analysis is the effect of the effectiveness of the torque control and the size of the study group (Deepak et al. studied only 10 people each in the study and control groups). The studies by Jena, Davoody and Rua had the highest level of sensitivity and heterogeneity.

Table 6. Heterogeneity analysis results; changes in the cumulative effects.

Study	D	Standard Error	Lower Limit 95% PU	Upper Limit 95% PU	p	Participation %	Change of Standard Error
Davoody et al. [15]	2.2687	0.6798	0.9363	3.6011	0.001	96.86%	−1.33%
Al-Sibaie et al. [16]	2.4392	0.7731	0.9240	3.9545	0.002	87.25%	12.21%
Deepak et al. [9]	2.8349	0.7060	1.4511	4.2186	0.000	86.14%	2.47%
Sadeka et al. [10]	2.0259	0.6500	0.7519	3.2999	0.002	90.61%	−5.66%
Al-Imam et al. [18]	2.6975	0.8454	1.0407	4.3544	0.001	86.22%	22.69%
Chen et al. [2]	2.2559	0.7052	0.8738	3.6380	0.001	92.31%	2.35%
Koyama et al. [19]	2.5864	0.7259	1.1637	4.0090	0.000	94.05%	5.35%
Lee et al. [11]	2.4437	0.7291	1.0146	3.8728	0.001	93.05%	5.83%
Tuncer et al. [17]	2.5522	0.7218	1.1374	3.9669	0.000	94.93%	4.76%
Xu et al. [8]	2.8121	0.7250	1.3912	4.2331	0.000	89.72%	5.22%
Ruan et al. [14]	2.5183	0.7198	1.1075	3.9290	0.000	95.39%	4.47%
Zhao et al. [12]	2.1462	0.6666	0.8396	3.4529	0.001	94.27%	−5.24%
Jena et al. [13]	2.5133	0.6987	1.1419	3.8807	0.000	99.20%	1.41%
Bez wyl.	2.4636	0.6990	1.1132	3.8140	0.000	100.00%	0.00%

D—difference in means.

The last column includes the change in standard error, which shows how the combined effect would change, i.e., how a given study affects heterogeneity. The research by Al-Immam and Al-Sibaie had the greatest impact on heterogeneity in this aspect.

The heterogeneity results are shown in Figures 3–5.

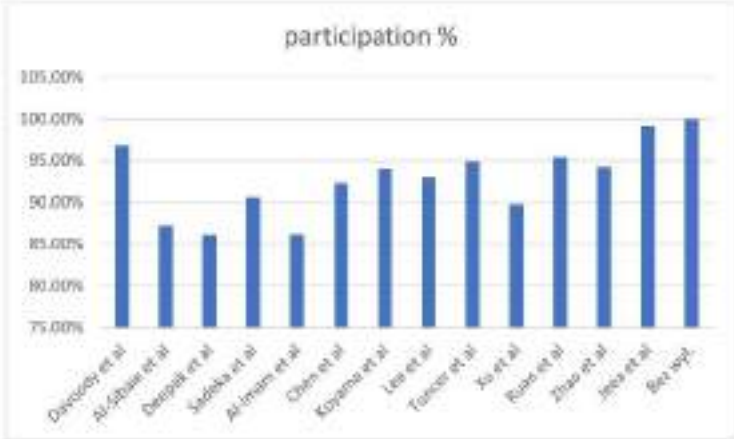

Figure 3. Heterogeneity analysis results by study.

Figure 4. Heterogeneity analysis: study impacts on heterogeneity.

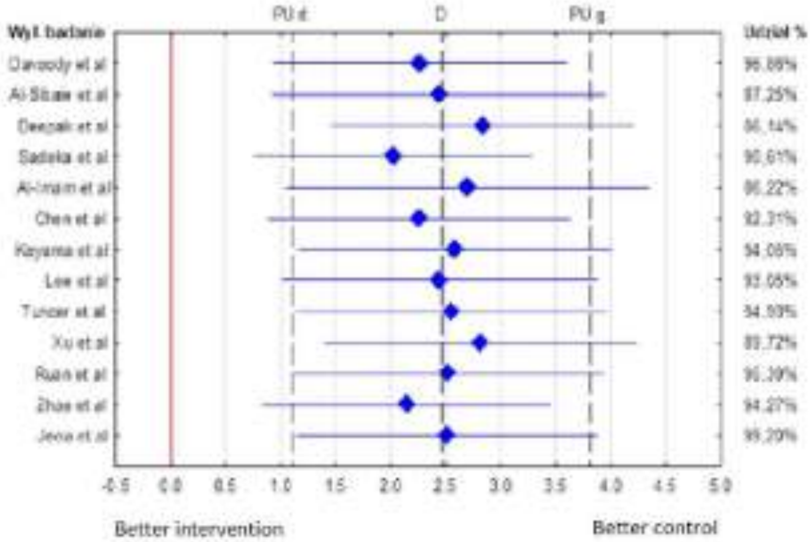

Figure 5. Heterogeneity analysis results.

6. Discussion

6.1. Risk of Bias

In most articles, the risk of bias was considered low due to the detailed, rigorous randomisation methods used. Only Tunçer et al. [17] described the risk of bias as moderate because the randomisation was not performed in a fully objective manner; instead, patients were assigned by the individual identification of their patient eligibility based on the criteria met.

The risk associated with the disclosure of group eligibility was considered low in all RCTs due to the use of opaque, sealed envelopes or other equivalent randomisation methods.

The use of specific treatments and the differences between them were known to both study participants and clinicians. Patients were aware of their participation in the study and signed an informed consent for proposed treatment. For this reason, the blinding of participants and personnel regarding treatment status was impossible, and the risk of bias for this criterion was identified as high.

Although the blinding of participants was not possible, the overall risk of bias was reduced in some studies by the blinding of assessors during the outcome analysis. In the articles by Al-Sibaie et al. [16], Al-Imam et al. [18], Chen et al. [2] and Tuncer et al. [17], assessors were not directly involved in the studies and did not know their purpose; therefore, the risk of bias was considered low. In the article by Sadeka et al. [10], assessors could easily define the purpose of the study (patients treated with vestibular or lingual orthodontic appliances), and thus blinding was not possible, and the risk was considered high. In contrast, Davoody et al. [15] provided no information on the blinding of assessors. However, they emphasised that assessors could easily identify patients in each group based on the analysis of cephalograms (presence or absence of mini-implants). A similar risk may have occurred in the study by Al-Sibaie et al. [16]. However, the authors clearly emphasised the blinding of assessors in their study. As it was difficult to determine the actual impact on risk of bias, it was finally considered uncertain in the article by Davoody et al. [15].

In all studies, complete data from patients were obtained and analysed. Therefore, the risk in this category was considered low.

In the articles by Davoody et al. [15] and Chen et al. [2], the authors highlighted the possibility of bias due to a reduction in the number of participants during the study. In the first study, the number of participants was reduced by approximately 30%, and in the second study by approximately 6%. Hence, the risk of selective reporting in the article by Davoody et al. [15] was identified as high, while in the article by Chen et al. [2] it was identified as moderate. In this category, the article by Tuncer et al. [17] also had a moderate risk. The reason was selectivity when selecting participants for the study.

Additional potential sources of bias were identified in several studies. In the article by Sadeka et al. [10], the authors highlighted that a different vertical position of mini-implants in the treatment groups, which was not included in the outcome analysis, may have influenced the inclination of the upper incisors. In contrast, Chen et al. [2] considered the influence of various anchorage methods that were used in individual patients as a potential source of bias in the results. Xu et al. [8] emphasised that the treatment of patients followed clinical standards, i.e., it was often tailored to the individual needs of patients and modified with the course of therapy. Therefore, a direct comparison of different treatments was not possible, which may have affected the lower statistical significance of the results obtained. Tuncer et al. [17] pointed out that the collection of molecular samples from patients started too late from the beginning of their study and that subsequent samples were taken at too-large intervals. In this case, however, these measurements were not relevant to this review. Finally, given the difficulty in determining the true impact of these limitations on the results obtained, the risk in the studies by Sadeka et al. [10], Chen et al. [2], and Xu et al. [8] was considered unclear.

The articles by Deepak et al. [9], Lee et al. [11] and Koyama et al. [18] received 4 points (maximum) for the patient selection criterion. Other articles (Ruan et al. [14], Jeea et al. [13]) lost 1 point due to lack of control. Because of confounding factors, also due to lack of control, the articles by Ruan et al. [14] and Jeea et al. [13] did not receive points, while other articles received the maximum number of points (2 points). Regarding the last criterion (evaluation of study effects), all articles lost 1 point due to the lack of blinding of assessors. Moreover, the study by Ruan et al. [14] lost 1 point due to a significant reduction in the number of patients eligible for the outcome analysis compared with the initial group. Finally, the study in question received 1 point in this category.

In addition to the discussed methods of controlling the axial inclination of incisors at the time of closing the post-extraction hatches, non-orthodontic methods are also mentioned such as corticotomy. According to the researchers, the use of these methods can also affect the rate as well as the range of the tilting of the incisors [21]. Adequate influence on the metabolism of specific areas of the compact bone can affect the distribution of the bone support of the teeth and thus the location of both the centre of resistance and the centre of rotation of the teeth. This may result in easier control of the torque of the front teeth during their retraction. Similarly, Zedeh et al. [21] showed, access to the subperiosteal vestibular incision tunnel (VISTA) for surgically assisted orthodontic treatment (SFOT) may improve the control of the axial position of the incisors during extraction therapy [21].

6.2. Outcome Analysis

There are many different methods for controlling root inclination during the retraction of the anterior teeth; however, most of them have not been sufficiently analysed, and hence, their effectiveness is not fully validated. According to the current systematic review, not all methods of incisor inclination control differ in terms of performance in a statistically significant way.

In terms of the methods of torque control that were reported in this systematic review, those with the highest statistically validated efficacy are worth analysing.

The use of corticotomy when retracting anterior teeth significantly reduces maxillary incisor inclination [19], and corticotomy may be relevant to root inclination control, i.e., incisions should be made on both the vestibular and palatal sides. Al Ihmam [19] revealed that torque control after corticotomy was good; that study had high-value evidence. In

Tunçer et al.'s study. [17], in which incisions were made only on the vestibular side, there was no statistically significant difference in the loss of control of incisor root inclination compared with a control group. Therefore, the study revealed that torque control was not good enough when limiting corticotomy to the vestibular side only; that study's evidence had moderate value. Given the above-mentioned analyses, it can be concluded that the possibility of torque control using corticotomy was proven; however, it requires additional studies on a larger group divided into control and treatment groups, and it requires a comparison between corticotomy performed only on the vestibular side and that performed on both the vestibular and palatal sides.

The use of TISADs during retraction also significantly reduces the maxillary incisor inclination (loss of control over the buccal–palatal inclination of the incisor roots). This is because the vector of force used for retraction approaches the centre of resistance of the teeth more closely than, e.g., during the standard retraction, where the force is applied to brackets placed on the maxillary molars. Furthermore, the standard retraction is often performed in two steps, which may further affect the greater retroclination of the incisors. This is confirmed by Al-Sibaie et al. [16] The value of the evidence for these studies is high. In this respect, it can be concluded that the torque control using TISAD is proven; however, as only one study was conducted, additional comparative studies will be necessary to unanimously accept this thesis.

When retracting the anterior teeth, it is more advantageous to use vestibular than lingual mechanics [10]. The en-masse retraction using mini-implants and arches on the vestibular side results in a reduction of maxillary incisor inclination compared with the same en-masse movement from the lingual access and mini-implants placed on the palate. In the latter, the force vector lies farther from the centre of resistance of the retracted segment, which causes the teeth to be inclined more strongly and torque control to become weaker. Those issues were addressed by Sadek et al. [10], whose study evidence had moderate value. A shortcoming of that study is that the authors did not consider the outcome analysis of the different vertical positions of the mini-implants in the analysed groups, which may affect the inclination of the upper incisors and make a precise comparison of torque controls impossible. With these concerns in mind, detailed studies taking into account the reproducibility of mini-implant placement should be conducted to obtain reliable findings that describe the effects of this type of anchorage and its placement on the final inclination of the incisor long axis. When considering the studies concerning the use of mini-implants to control incisor inclination during retraction by acknowledging some imperfections in the studies conducted but taking into account their high-value evidence, this method can be considered proven.

The use of management protocols such as the intrusive arch [10,15] or the PASS [7] system during incisor retraction should be mentioned. Brackets placed on the molars in the PASS system have an extra slot with an inclination angle of 25°. The insertion of an extra arch into this slot and its attachment to the incisors have a similar effect to the use of an intrusive arch: It strengthens the anchorage in the molar region and causes the intrusion of the incisors and their protrusion, thus increasing the root inclination control during retraction. The study used an intrusive arch both combined with mini-implants [10] and without mini-implants [15], with better results for torque control when a skeletal anchorage was included. Nevertheless, the use of the intrusive arch alone in anterior teeth retraction [15] turned out to be more effective in controlling root inclination compared with isolated skeletal anchorage [16]. This emphasises the role of the control of the vertical dimension during retraction in maintaining the correct incisor root inclination. The evidence from the studies in question was of moderate value. Due to the small sizes of the treatment groups, it should be concluded that the above-mentioned methods are effective in terms of incisor torque control; however, further studies of larger groups are necessary to unequivocally prove the superiority of these methods over others.

The use of class I elastics results in less incisor inclination during retraction compared with the use of a power chain for this purpose [12]. This difference is probably due to the significantly lower force acting on the anterior segment when using intramaxillary elastics (approx. 100 g) instead of a power chain (approx. 250 g).

The effect of age on the degree of incisor inclination control is probably minor, as suggested by Ruan et al. [14]. Although the retroclination of the incisors in that study was greater in the adult group, there was no statistically significant difference between groups at different ages. The value of evidence for that study is considered low, and thus the age criterion cannot be considered a factor that influences the change in incisor inclination during orthodontic treatment involving premolar extraction.

The statistical analysis revealed that the use of additional components that control root inclination resulted in less incisor inclination during retraction compared with closing gaps after missing teeth without the use of these methods (Table 4). Nevertheless, not all methods were equally effective. The greatest difference between the control group and the treatment group assisted by control mechanisms of root inclination was found for the standard two-step retraction using the extra-intrusive arch (Table 4). In terms of comparing the effectiveness of torque control during en-masse retraction in various studies and ranking it from highest to lowest, the following order of studies was obtained: Sadeka et al. [10], Li et al. [12], Chen et al. [2], Al-Sibaie et al. [16], and Al-Imam et al. [18] (Table 1). It should be noted that the scientific credibility of those studies, ranked from largest to smallest, had a different order: Al-Imam et al. [18], Al-Sibaie et al. [16], Chen et al. [2], Sadeka et al. [10], Davoody et al. [15] and Zhao et al. [12] (Tables 2 and 3).

The effect on the combined result of the statistical analysis also varied. In descending order from the highest aggregate score to the lowest, the ranking of studies was as follows: Al.-Imam et al. [18], Al-Sibaie et al. [16], Sadeka et al. [10], Chen et al. [2], Zhao et al. [12] and Davoody et al. [15] (Table 4). In conclusion, the results of studies that prove the high effectiveness of root inclination control are, unfortunately, often associated with low statistical reliability. However, it can be assumed that the use of corticotomy involving incisions made on both the vestibular and palatal sides, the en-masse retraction of the anterior teeth using TISAD placed on the vestibular side, and the use of the extra-intrusive arch provide the best incisor torque control. This does not preclude the need for more detailed studies of larger control groups to demonstrate greater differences in terms of methods used.

7. Limitations

The main limitations of this review include the time-period restriction, the last 10 years, and the restriction to English-language publications. This may have had an impact on the risk of statistical bias in the publication. Another limitation was the low number of clinical trials (RCTs and CCTs) that analysed the topic addressed. The inclusion of only articles that describe studies concerning the torque value both before and after orthodontic treatments proposed according to specific treatment protocols also became a limitation.

In terms of studying the effectiveness of different methods of teeth retraction, the presence of a control group proved to be very important. By definition, a control group should not receive treatment. Therefore, it is not possible to establish a control group when examining the change in root inclination of the anterior teeth because among other reasons, orthodontic treatment cannot be dispensed with after an extraction for orthodontic indications. Consequently, this study is a comparison of different methods of torque control. In the article selection process, some clinical trials were considered equivalent to control studies because the results showed a comparison of treatment groups despite differences in the article description. The review also included one article that was a retrospective study but met the requirements for CCTs. The statistical analysis revealed that a significant SD in the absence of large study and control groups casts doubt in many articles on the reliability of results obtained. This explains the need for further studies, especially RCTs with more homogeneous groups of sufficiently large size.

8. Conclusions

The analysed studies indicate that corticotomy or orthodontic mini-implants are the most effective and scientifically proven methods of incisor inclination control during incisor en-masse retraction [16,19]. The use of both vestibular mechanics and an extra slot in brackets placed on the molars, which creates an effect that is similar to that of the intrusive arch, was studied in protocols with unclear risk of bias where various factors could affect the reliability of the results [7,10,15]. In contrast, the use of light force of intramaxillary elastics was only analysed in a non-randomised clinical trial. Therefore, the conclusions of the present study should be interpreted with caution (Table 3). The patient's age also seems to be irrelevant to torque control [14].

Although all studies reported that the incisors were inclined after retraction, it should be noted that extraction is often performed when the incisors are excessively inclined. Hence, treatment aims to partially straighten the incisors and slight incisor inclination cannot be considered as a lack of control of the buccal-palatal inclination of incisor roots provided that it is not excessive. To give a definitive answer to the question concerning which method most effectively controls torque during anterior teeth retraction, further high-quality RCTs studies.

Author Contributions: M.S., E.A. and B.K. were authors of research concept; M.N., J.K. and A.E.K. collected the data and were main co-authors in terms of writing the manuscript. M.S., E.A.,M.N. and J.L. analysed and interpreted the data. M.N., M.W., J.K., A.E.K. and M.S. created tables and prepared references. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PICO	Population, Intervention, Comparison, Outcome
RCT	Randomised Clinical Trial
CCT	Controlled Clinical Prospective Trial
ROBINS-I	Risk of Bias in Non-randomized Studies of Interventions
QAS	Quality Assessment Scale

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8.4. Publikacja 4

Journal of *Clinical Medicine*

MDPI

Systematic Review

Bone Remodeling of Maxilla after Retraction of Incisors during Orthodontic Treatment with Extraction of Premolars Based on CBCT Study: A Systematic Review

Anna Ewa Kuc [1,*], Jacek Kotula [1], Jakub Nawrocki [1], Maria Kulgawczyk [2], Beata Kawala [1], Joanna Lis [1] and Michał Sarul [3]

[1] Department of Dentofacial Orthopedics and Orthodontics, Wroclaw Medical University, Krakowska 26, 50-425 Wroclaw, Poland; j_kotula@poczta.onet.pl (J.K.); beata.kawala@umw.edu.pl (B.K.); joanna.lis@umed.wroc.pl (J.L.)
[2] Dental Star Specialist Aesthetic Dentistry Center, 15-215 Bialystok, Poland; kulgawczyk.m@gmail.com
[3] Department of Integrated Dentistry, Wroclaw Medical University, 50-425 Wroclaw, Poland; michal.sarul@umw.edu.pl
* Correspondence: annaewakuc@wp.pl

Abstract: Background: Incisor retraction is often a crucial phase in ongoing orthodontic treatment, with significant implications for alveolar remodeling mechanisms. There are two prevailing theories which seek to explain this. According to the first, teeth move with the bone, while according to the second, teeth move within the bone. This systematic review seeks to assess morphometric changes in the maxillary alveolar process resulting from incisor retraction following premolar extraction and to evaluate the potential for bone remodeling associated with orthodontic movement. **Methods:** The study was conducted following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The following electronic databases were searched: PubMed, Google Scholar, Web of Science EMBASE and the Cochrane Central Register of Controlled Trials. The databases were searched using the following keywords: "Bone remodeling and retraction of incisors", "Alveolar bone and incisor retraction", "Bone thickness and incisor retraction", and "Bone changes and orthodontic treatment". Search filters were utilized to identify relevant papers and articles written in English and published during the last 10 years. Based on the information provided in their abstracts, papers and articles were selected according to the following criteria: randomized clinical trials (RCTs), controlled clinical prospective trials (CCTs), and retrospective studies. Articles unrelated to the study's scope or failing to meet inclusion criteria were excluded. These generally comprised individual case reports, case series reports, literature reviews, experimental studies, studies with limited data (including conference abstracts and journal writings), studies involving an unrepresentative group of patients (less than 10 patients), studies concerning patients with syndromes, and animal experiments. The remaining articles which were deemed relevant underwent comprehensive reference review and such journals as the American Journal of Orthodontics, Dentofacial Orthopedics, International Orthodontics, Journal of Clinical Orthodontics, and Angle Orthodontist were manually searched. **Results:** Seven articles meeting the inclusion criteria articles were selected for final evaluation, with a total of 284 participants, including 233 women and 51 men. During the analysis of the results included in the publications, a lack of homogeneity was observed, rendering a reliable statistical analysis and heterogeneity assessment unobtainable. Noteworthy disparities in methodologies and measurements posed a risk of drawing inappropriate conclusions. Consequently, emphasis was placed on qualitative analysis, emphasizing the need for standardization in future studies of a similar nature, to enable valid and comparable analyses. **Conclusions:** The research findings incorporated in this review demonstrate that significant bone loss occurs because of incisor retraction, which diminishes distance between the bone surface and the root surface on the palatal aspect. The magnitude of this change may vary, contingent upon both the extent of incisor displacement and alterations in their inclination, thereby affecting the positioning of the root tips. This change is significantly higher in adults than in growing adolescents. The rationale behind this assertion lies in the widely recognized phenomenon of declining cellular activity with advancing age. The decrease in the speed and intensity of cellular

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changes may explain the diminished capacity for remodeling as patient age increases. There is ongoing discourse regarding alterations in the volume of bone on the labial aspect of the alveolar process. Further research is necessary to measure whether bone remodeling during orthodontic movement is contingent upon other factors, such as the speed and biomechanics of retraction, the level of applied orthodontic force, and the patient age.

Keywords: bone remodeling; retraction; orthodontic treatment; CBCT study

1. Introduction

Orthodontic treatment encompasses not only the correction of malocclusion and enhancement of dental arch aesthetics, but also the preservation or restoration of optimal function and periodontal tissue health [1]. Smooth movement of teeth to their planned and stable position is contingent upon sufficient support of the alveolar process [2]. When planning tooth positioning, the anatomical limitations of the alveolar bone should be considered to avoid iatrogenic consequences in the form of dehiscence, fenestration of the alveolar process, or resorption of tooth roots [3].

There are many theories regarding bone remodeling during orthodontic tooth movement. Among them, two concepts are widely regarded as the most dependable: tooth movement "with the bone" and tooth movement "through the bone." If, where the force is applied, resorption occurs in the pressure zone, and bone apposition occurs in the traction zone, then we are dealing with the movement of the tooth "with the bone". The tooth then remains surrounded by the alveolar bone. In the case of tooth movement "through the bone", we are dealing with an imbalance between bone resorption and apposition. In this situation, the tooth violates the bone boundary, remaining partially beyond its reach. The morphology of periodontal tissues, differences in bone density, inclination and position of teeth, and direction and magnitude of orthodontic force determine the type of bone reaction [4–7].

Retraction is a common procedure performed during orthodontic treatment, especially in the anterior maxilla [8]. Patients with a narrow alveolar bone width constitute a group that may show significant loss of periodontal tissue, especially alveolar bone, during incisor retraction [9]. The thickness of the alveolar bone around the incisors is an important factor in determining the direction of tooth movement. Morphometric assessment of the alveolar bone should be an indispensable element when planning orthodontic treatment, including changing the position of the incisors to avoid undesirable effects in the form of bone loss, dehiscence, fenestration, or root resorption [10]. Moreover, previous research has confirmed that in the group of orthodontically treated patients, the incidence of various types of bone dehiscence is higher than in the general population [3].

The use of cone beam computed tomography (CBCT) allows for a detailed assessment of the dimensions of the alveolar bone. Owing to their two-dimensional nature, commonly used cephalometric images exhibit significant limitations in periodontal tissue assessment [11,12]. Two-dimensional images are characterized by overlap, magnification and consequent distortion of anatomical structures, rendering accurate assessment of morphometric bone changes before and after orthodontic treatment unfeasible. The three-dimensional imaging method (CBCT) eliminates the problem of overlapping anatomical structures, allowing for detailed qualitative and quantitative verification of the alveolar bone and assessment of changes in the position of teeth. Imaging using CBCT can provide a detailed and reliable presentation of alveolar bone dimensions and is currently the best tool for planning orthodontic tooth movements [1,4,9]. Given the radiation risk and the imperative for patient radiological protection, careful consideration of the cost vs benefits associated with heightened tissue radiation absorption should underpin CBCT diagnostic planning.

The aim of this study was to present the results published in scientific publications assessing morphometric changes in the anterior part of the maxillary alveolar bone that occurred because of orthodontic retraction of incisors after premolar extraction, based on CBCT images. The null hypothesis was that tooth movement during retraction follows the "through the bone" pattern of movement.

2. Materials and Methods

2.1. Selection of Material

This systematic review has been registered in the PROSPERO database under the identification number CRD42023406039.

The study was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The study design was defined using the following PICO format:

Population (P): patients with full permanent dentition, encompassing both adolescents and adults;

Intervention (I): orthodontic extraction treatment with a fixed brace using incisor retraction;

Comparison (C): evaluation of the dimensions of the maxillary alveolar process before and after incisor retraction;

Outcome (O): identification of statistically significant/non-significant differences in the dimensions of the jaw alveolar process before and after treatment.

Electronic databases, including PubMed, EMBASE, and the Cochrane Central Register of Controlled Trials, were searched using the following keywords:

- Bone remodeling and retraction of incisors;
- Alveolar bone and incisor retraction;
- Bone thickness and incisor retraction;
- Bone changes and orthodontic treatment.

Search filters were utilized to identify relevant papers and articles written in English and published during the last 10 years (before this date, only studies conducted on cephalometric images were detected). Independent searches of databases were conducted by the authors (A.E.K. and J.K.). Following the removal of duplicates, the titles were reviewed for relevance to the subject of this systematic review. Titles that passed this initial screening were then subjected to a detailed evaluation. During this review process, the authors were unaware of each other's selections. Any discrepancies were discussed until an agreement was reached, with the involvement of the third author (MS) if needed. Based on the information provided in abstracts, papers and articles were selected according to the following criteria: randomized clinical trials (RCTs), controlled clinical prospective trials (CCTs), and retrospective studies. Articles unrelated to the study's scope or failing to meet inclusion criteria were excluded. These generally comprised individual case reports, case series reports, literature reviews, experimental studies, studies with limited data (including conference abstracts and journal writings), studies involving an unrepresentative group of patients (less than 10 patients), studies concerning patients with syndromes, and animal experiments. The remaining articles which were deemed relevant, underwent comprehensive reference review and such journals as the American Journal of Orthodontics, Dentofacial Orthopedics, International Orthodontics, Journal of Clinical Orthodontics, and Angle Orthodontist were manually searched (Figure 1). The following data were extracted from reviewed articles: year of publication, group size, patient malocclusion, characteristics of treatment and control groups, the assessment method, and results.

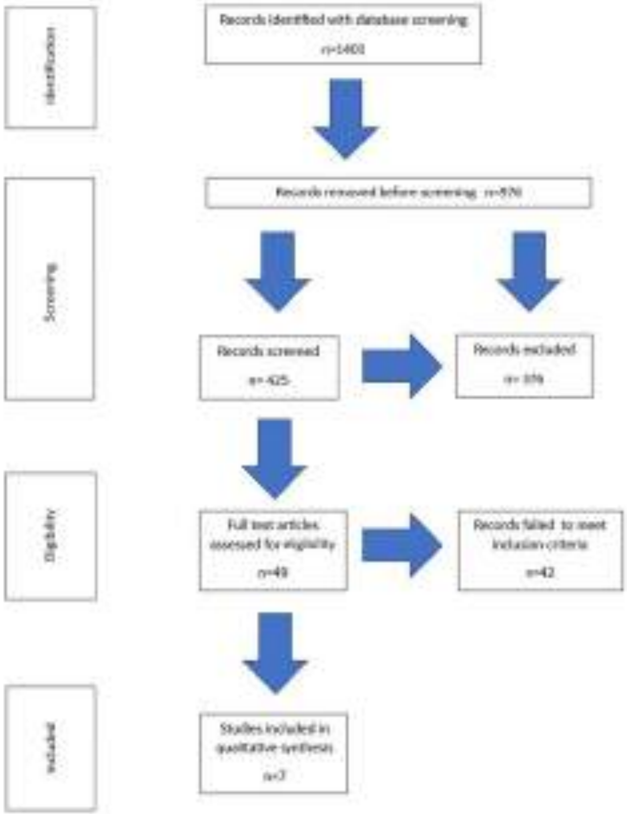

Figure 1. PRISMA flow chart.

2.2. *Risk of Bias*

The collected articles were subjected to risk of bias analysis according to Liu et al. [13], utilizing the ROBINS-I tool.

The quality and internal relevance (level of reliability) of each publication were rated as high, moderate, or low. Levels of evidence and criteria for evidence synthesis were as follows:

- High level of evidence: Studies were classified as having a high level of evidence if they met all the following criteria:
  - An independent blind comparison of the test and reference methods was performed (in Figure 2, marked as A).
  - The population was described in such a way that the disease status, prevalence, and severity of the disease were clear. The spectrum of patients was like the spectrum of patients in whom the research method would be used in clinical practice (marked as B in Figure 2).
  - The results of the test method had no impact on the decision to use the reference method (marked as C in Figure 2).
  - The test and reference methods are well described in technical and implementation terms (marked as D in Figure 2).
  - The assessments (observations and measurements) performed were well described, providing the diagnostic criteria used as well as information and instructions for observers (marked as E in Figure 2).

- ○ The repeatability of the test method is described for one observer (intra-observer performance) and several (minimum 3) observers (inter-observer performance) (marked as F in Figure 2).
- ○ The results are presented as relevant data needed for the necessary calculations (marked as G in Figure 2).

- Moderate level of evidence: Studies were rated as having a moderate level of evidence if any of the above criteria were not met. On the other hand, a study showing any of the deficiencies described below was rated as low evidence.
- Low level of evidence: Studies were considered to have a low level of evidence if they met any of the following criteria:
    - ○ Assessment of the test and reference methods was independent (A).
    - ○ The population has not been clearly described, and the spectrum of patients is disturbed (B).
    - ○ The results of the test method influenced the decision to use the reference method(C).
    - ○ The test, reference method, or both, were not well described (D).
    - ○ The results were not well described (E).
    - ○ The repeatability of the research method was not described or was described only for one observer (F).
    - ○ The results may have a systematic bias (H).
    - ○ The results were not presented in a way that would enable the calculation of effectiveness (G).

Figure 2. The risk of bias analysis of articles evaluating bone remodeling of maxilla after retraction of incisors during orthodontic treatment with extraction of premolars [14–20].

The evaluation of the conclusions according to the degree of evidence of articles discussing bone remodeling of maxilla after retraction was performed using the risk of bias table in RevMan 5.3 for RCTs (Figure 3).

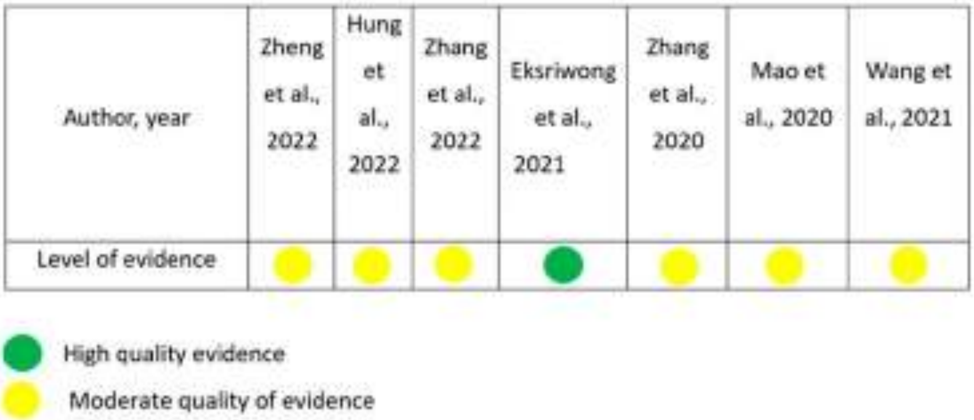

Figure 3. The evaluation of the conclusions according to the degree of evidence of articles discussing bone remodeling of the maxilla after retraction [14–20].

2.3. *Statistical Analysis*

During the analysis of the collected data, a significant limitation was encountered impeding the execution of a dependable statistical analysis and the evaluation of heterogeneity. This impediment stemmed from the lack of coherence in results across individual studies. Differences in methodology, patient inclusion criteria, and methods of measuring and classifying outcomes were sufficiently defined to preclude any endeavor to amalgamate these data, thus risking fallacious deductions.

Without consistent and comparable data, the risk of distorting the results of statistical analysis increases significantly, which may consequently affect the credibility and scientific value of the results. Consequently, a qualitative analysis of available data was chosen as the basis for conclusions, with an emphasis on advocating for standardization in future research endeavors, in order to facilitate precise and reproducible statistical analysis.

3. Results

Keyword entries yielded 1401 abstracts. In total, 49 articles were initially confirmed as eligible for systematic review and were analyzed in detail. Out of the 49 full-text articles assessed for eligibility, 42 articles were rejected because the studies they contained did not relate to the method involving premolar extraction, or they solely relied on cephalometric analysis. Ultimately, seven articles were selected. The full selection process is shown in Figure 1.

3.1. Groups

3.1.1. Group Size

The study group included 284 people, 233 women and 51 men. The average group size was 40 people. The largest group was found in Zhang's article—72 people. The smallest group was included in Eksiwrong's study—17 people (Table 1).

Table 1. Studies included in the systematic review.

Reference	Patients	Groups	Age	Patients Malocclusion	Treatment Method	Assessment Method	Results
Zheng Y. et al., 2022 [14]	N = 72 (F = 72)	G1 (minor) = 36 G2 (adult) = 36	G1 (minor) 11–16 years old G2 (adult) 18–35 years old	Bimaxillary protrusion with class I malocclusion	Extraction of four first Premolars, Self-ligating brackets	Pre- and post-treatment CBCT and late cephalograms	Changes of the alveolar bone thickness at the crestal, mid-root and apical third in the central incisor (adults): Labial: La3: 0.16 ± 0.44 La6: 0.09 ± 0.46 La9: 0.26 ± 0.65 Palatal: Pa3: −1.48 ± 0.79 Pa6: −1.70 ± 1.41 Pa9: −1.39 ± 2.67 Changes of the alveolar bone thickness at the crestal, mid-root and apical third in the central incisor (minors): Labial: La3: 0.38 ± 0.47 La6: 0.29 ± 0.42 La9: 0.32 ± 0.70 Palatal: Minors: Pa3: −0.88 ± 1.21 Pa6: −0.82 ± 1.82 Pa9: −0.31 ± 2.25
Hong et al., 2022 [15]	N = 24 (M = 6, F = 18)	G1 = 24	Mean ± SD 19.29 ± 4.64 years	Bimaxillary protrusion with skeletal Class I or II	Extraction of four first premolars, Incisor retraction treatment by sliding mechanics with microimplants in the maxilla	Pre- and post-treatment CBCT and late cephalograms	Changes of the alveolar bone thickness (ABT): Labial ABT: 0.59 ± 0.93 Palatal ABT: −0.94 ± 1.18
Zhang F. et al., 2020 [16]	N = 36 (M = 16, F = 20)	G1 = 36	Mean ± SD 20.6 ± 2.4 years 18–31 years old	Skeletal class I with bimaxillary protrusion	Extraction of four first premolars	Pre- and post-treatment CBCT and late cephalograms	Comparison of Alveolar Bone Thickness Before (T0) and After Orthodontic Treatment (T1): Labial side L1: T0: 0.70 ± 0.34 T1: 0.67 ± 0.58 L2: T0: 0.78 ± 0.30 T1: 0.94 ± 0.44 L3: T0: 0.88 ± 0.30 T1: 1.07 ± 0.54 L4: T0: 1.09 ± 0.46 T1: 1.50 ± 0.73 L5: T0: 1.87 ± 0.73 T1: 2.29 ± 1.36 Lingual side L1: T0: 1.23 ± 0.58 T1: 0.51 ± 0.58 L2: T0: 2.03 ± 0.87 T1: 1.06 ± 0.56 L3: T0: 2.89 ± 1.34 T1: 1.79 ± 1.49 L4: T0: 4.09 ± 1.33 T1: 2.86 ± 1.82 L5: T0: 5.97 ± 1.70 T1: 4.55 ± 2.37
Eksriwong et al., 2021 [17]	N = 17 (F = 17)	G1 = 17	18 to 30 years old	(-)	Extraction of the maxillary first premolars, Incisor retraction was performed using T-loop	Pre- and post-treatment CBCT	Alveolar Bone changes (CT0–CT1) at crestal, mid-root and apical level of the maxillary Incisor Roots: Labial: Crestal: −1.2 ± 1.1 Mid-root: −0.9 ± 1.3 Apical: −0.8 ± 0.9 Palatal: Crestal: −0.2 ± 0.5 Mid-root: −0.1 ± 0.7 Apical: −0.2 ± 0.4

Table 1. Cont.

Reference	Patients	Groups	Age	Patients Malocclusion	Treatment Method	Assessment Method	Results
Zhang C. et al., 2022 [16]	N = 63 (M = 10, F = 53)	G1 = 63	Mean ± SD 24.41 ± 5.80 years 18–42 years old	CII	Extraction of four first premolars	Pre- and post-treatment CBCT	The thickness changes in the maxillary alveolar bone at crestal, mid-root, and apical levels: Labial: A1: T0: 3.38 ± 0.76 T1: 3.13 ± 0.74 A2: T0: 3.71 ± 0.74 T1: 3.39 ± 0.77 A3: T0: 3.24 ± 1.36 T1: 2.75 ± 1.10 Palatal: B1: T0: 1.42 ± 0.69 T1: 1.41 ± 0.82 B2: T0: 2.91 ± 1.30 T1: 2.86 ± 1.38 B3: T0: 7.12 ± 1.76 T1: 6.74 ± 2.33
Mao et al., 2020 [19]	N = 38 (M = 7, F = 31)	G1 = 38	15–33 years old Mean age 19.52 years	Bimaxillary protrusion with class I malocclusion	Interactive self-ligating brackets, retraction using TADs	Pre- and post-treatment CBCT	The thickness changes in the maxillary alveolar bone at the crestal, mid-root, and apical third: Labial: Crestal: T0: 0.6 ± 0.3 T1: 0.8 ± 0.3 Mid-root: T0: 0.7 ± 0.2 T1: 0.9 ± 0.4 Apical: T0: 0.9 ± 0.3 T1: 1.0 ± 0.6 Palatal: Crestal: T0: 1.6 ± 0.4 T1: 0.7 ± 0.8 Mid-root: T0: 2.9 ± 0.8 T1: 2.2 ± 1.4 Apical: T0: 4.4 ± 1.4 T1: 4.2 ± 1.8
Wang et al., 2021 [20]	N = 34 (M = 12, F = 22)	G1 = 34	Mean ± SD 14.20 ± 1.24 years	Bimaxillary protrusion	Extractions of the four first premolars, miniscrews for maximum anchorage	Pre- and post-treatment CBCT	Comparison of mean labial and lingual alveolar bone thickness at T1 (pre-treatment), T2 (post-treatment) and T3 (retention phase) of the central incisor: Labial: Cervical level: T1: 1.93 ± 0.32 T2: 1.65 ± 0.57 T3: 1.61 ± 0.59 Middle level: T1: 1.84 ± 0.58 T2: 1.95 ± 1.02 T3: 1.74 ± 0.52 Apical level: T1: 4.06 ± 1.35 T2: 4.07 ± 1.84 T3: 3.78 ± 1.16 Palatal: Cervical level: T1: 2.66 ± 0.77 T2: 1.88 ± 1.01 T3: 2.15 ± 0.60 Middle level: T1: 4.49 ± 1.58 T2: 3.75 ± 1.88 T3: 3.86 ± 1.34 Apical level: T1: 7.95 ± 1.87 T2: 7.33 ± 2.21 T3: 7.14 ± 1.74

3.1.2. Population

In the majority of studies, the participants were adult patients; however, in the studies by Zheng et al., Mao et al., and Wang et al. adolescents constituted the study cohort. In total, 284 individuals were enrolled for the study, comprising 233 women and 51 men (Table 1).

3.1.3. Intervention

The inclusion criteria for patients in all of the analyzed studies were as follows: extraction of the first maxillary premolars, absence of significant medical history, no periodontal disease, no history of dental trauma, and the performance of CBCT before and after orthodontic treatment. Wang et al., Zheng et al., and Hung et al. also included patients with mild crowding in the arch in their studies. The treated patients underwent extraction of the maxillary first premolars to obtain space for the retraction of the incisors and canines. Skeletal anchorage was used in the studies by Hung et al., Mao et al., and Wang et al. Additionally, Mao et al. and Zheng Y. et al. used self-ligating brackets. Eksiwong et al. used a T-loop archwire for retraction purposes (Table 1).

3.2. *Outcome*

The main parameter was a change in the thickness of the maxillary alveolar bone on the vestibular and palatal sides.

In all studies, a correlation between incisor retraction and changes in alveolar process thickness was observed (Table 2).

Table 2. Bone remodeling after intervention.

	Zheng Y. et al., 2022 [14]	Hung et al., 2022 [15]	Zhang C. et al., 2022 [16]	Eksiwong et al., 2021 [17]	Zhang F. et al., 2020 [18]	Mao et al., 2020 [19]	Wang et al., 2021 [20]
Labial resorption					x		
Palatal resorption	x	x	x	x	x	x	X
Apposition/no labial resorption	x	x	x	x		x	X
Apposition/no palatal resorption				x			

As a result, in all studies, maxillary bone resorption occurred on the palatal side during incisor retraction. The greatest resorption was observed on the palatal side among a group of adults in Zheng's study (−1.59) (Table 1). The results of statistically significant tests are presented below:

Zheng et al. demonstrated bone resorption on the palatal side both in the retraction group of adults (average −1.46) and adolescents (average −0.64); however, resorption was much greater in adults. Although bone thickness increased on the vestibular side in both groups, the increase was smaller in adults (mean +0.17) than in adolescents (mean 0.33) [14].

Hung et al. showed resorption on the palatal side (average −0.94) and an increase in bone thickness on the vestibular side (average 0.55); however, they did not observe changes in the total thickness of the alveolar bone before and after orthodontic treatment (average −0.27). Additionally, they noticed a significant bone reduction both vertically and horizontally on the palatal side [15].

Zhang C. et al. showed alveolar bone resorption both on the vestibular side at all levels (average −0.35) and on the palatal side at the middle level (average −0.35). (Figure 4) They did not notice any difference in changes depending on gender, age, or duration of orthodontic treatment [16].

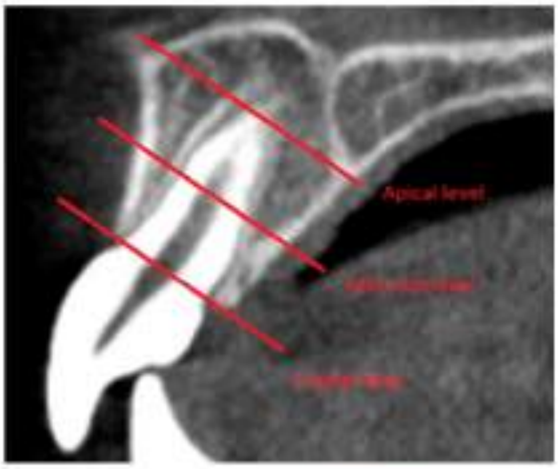

Figure 4. Three levels of measurements [14,16,17,19,20].

Eksiwong et al. noticed that on the vestibular side, the ratio of remodeling consisting of bone resorption to the amount of tooth movement is 1:1, while on the palatal side, it is 0.2–0.4. The bone on the palatal side does not seem to change, and only the distance between the root and the lamina compact palatine changes. However, the inclination of the incisor root is the only factor influencing the change in bone volume [17].

Zhang F. et al. demonstrated significant changes in the shape and thickness of the alveolar bone after incisor retraction. The process becomes thicker on the vestibular side, except at level 1. Bone resorption occurs on the palatal side (average −1.09) [18].

Mao et al. noticed that on the vestibular side, there is an increase in alveolar bone after retraction or it does not change (on average 0.1), with simultaneous bone resorption at all levels on the palatal side (on average −0.6) and a decrease in its height between the T0 and T1 levels. The greatest bone resorption was found at the crestal level on the palatal side (average −0.9) (Figure 4). They showed correlations between the displacement of the incisor root apex and bone resorption on the palatal side [19].

Wang et al. did not notice any changes in bone thickness on the vestibular side (average 0.1), but on the palatal side, they found a significant decrease in bone thickness (average −0.7). However, after a retention period of 18–24 months, bone reconstruction took place at the L1 level, with no changes at the other levels. (Figure 4) Additionally, they showed a significant reduction in the height of the process on both sides after orthodontic treatment, which persisted after the retention period [20].

4. Discussion

Analysis of the Results

There has been a debate for many years about whether the biomechanics of orthodontic treatment cause the tooth to move in the bone or with the bone [21]. This is an important aspect when it comes to maintaining healthy periodontium and reducing the risk of incisor resorption in the case of extraction treatment of bimaxillary dentoalveolar protrusion, camouflage treatment in the case of class II malocclusions, or treatment of open bites. The use of maximum anchorage after premolar extraction and incisor retraction can significantly improve lip position, facial profile, and occlusion [22]. A large range of incisor displacement, unfortunately, comes with a high-risk of exceeding the so-called bone envelope, causing contact between the incisor roots and the palatal plate, the lamina compacta of the incisive canal, which may result in resorption of the incisor roots or fenestrations of the palatal plate [23,24]. Many factors, such as the amount of orthodontic force applied, the speed of tooth movement, the type of orthodontic movement—uncontrolled inclination, controlled inclination, or axial shift—as well as the patient's age, influence bone remodeling [19]. The alveolar bone in young patients is very flexible during growth and quickly adapts to changes, while in adult patients, remodeling is significantly limited. This may be related to a reduction in the number of progenitor cells, reduced blood supply and density of fibroblasts, or a reduced ability of osteoblasts to proliferate and form bone [19]. Knowledge of the processes occurring during incisor retraction combined with the ability to precisely visualize the pre-treatment condition based on CBCT examinations allows for the development of an optimal orthodontic treatment plan for periodontal tissues and the bone envelope.

Undoubtedly, all studies analyzed in this review showed significant changes in the thickness of the maxillary alveolar bone after orthodontic treatment associated with incisor retraction. In all studies, a decrease in bone thickness was observed on the palatal side, while on the vestibular side, the results are varied and show both atrophy and gain. It has also been shown that the greater the distal root movement, the greater the changes in the volume of the alveolar process. Moreover, in children or adolescents, these changes are smaller, and bone resorption on the palatal and vestibular sides is not as severe as in adult patients. However, it was not observed that gender or the duration of orthodontic treatment had an impact on the changes occurring in the bone. Most studies are retrospective studies of medium evidentiary value. However, Eksiwrong's research, as a prospective study, is characterized by high evidentiary value.

The research of Zheng et al. turned out to be very valuable and undoubtedly showed that age has a huge impact on changes in the volume of the alveolar process during retraction. Greater bone loss on both the vestibular and palatal sides was observed in adult patients than in adolescent patients. This suggests that orthodontic movement in adolescents may, according to the theory, take place with the bone, while after the end of growth in adults, the same movement will take place through the bone. This may explain the changes occurring during retraction in the alveolar process and guide treatment planning in adults, depending on the bone volume in the vestibular and lingual dimension. Moreover, the vestibular and palatal laminae can be treated as walls limiting the range of tooth movement. The results of these tests may also be an indication to start treatment as early as possible when bone remodeling capabilities allow for minimizing side effects or complications in the form of bone and incisor root resorption [14].

Research by Hung et al. showed no change in the total vestibulopalatal volume of the alveolar bone after incisor retraction. There was bone reduction on the palatal side, but this was accompanied by bone growth on the labial side. Such results indicating the lack of narrowing of the alveolar process after orthodontic treatment may be the result of the use of mini orthodontic implants for the axial retraction of the incisors. In these biomechanics, the incisors are not only retracted but also controlled in the vertical dimension, which may explain the lack of change in bone thickness at the appropriate levels. However, these studies confirmed the correlation between the extent of distal displacement of the incisors and bone thinning on the palatal side [15].

The research by Zhang C. et al., on the other hand, indicated that bone resorption occurs on both the labial and palatal sides as an end result of incisor retraction during extraction treatment. They did not observe bone regeneration on either side. However, the results may be subject to a risk of error since the measurements were made 2 weeks after the end of treatment. However, the processes of new bone formation take longer and are slower than bone resorption. Moreover, the study participants were exclusively adults. This may confirm that age has an impact on changes in alveolar process volume after orthodontic treatment and that the range corresponds to the amount of bone resorption [16].

Subsequent measurements performed by Eksriwong were of high evidentiary value, as they were prospective control studies, and they questioned the dependence of changes in the volume of the alveolar process on the extent of retraction and correlated it with the change in the inclination of the incisors. Contrary to previous studies by Cangialosi [25], the bone remodeling on the labial side occurred in a 1:1 ratio in response to tooth displacement, while on the palatal side, the bone did not change. Only the distance between the root and the palatal lamina compacta changed due to tooth movement. In these measurements, only the inclination of the incisors was a factor influencing the changes in the maxillary alveolar process. The advantage of the study was the use of skeletal structures as reference points for the measurements taken. The incisor axis can only be referenced if the change in inclination is less than 10°. In other cases, a change in inclination may falsify the measurement results [17]. The results obtained in this study align with Handelman's research [26], which shows that the palatal plate of the maxillary alveolar process ought to be regarded as an orthodontic barrier not to be breached. The stability of the palatal cortical plate, regardless of the range of incisor movement, indicates that movement should be planned within the range of the process. Uncontrolled mechanics may predispose to fenestration, dehiscence of the alveolar process, and resorption of the incisor root tips as a result of greater retraction than the initial position of the palatal lamina compacta [17].

Interesting results were presented by Zhang F. et al. They showed that both on the labial and palatal sides, the alveolar bone drifts with the movement of the tooth, and the lingual bone crest moves apically. There is a significant reduction in bone volume on both sides, and on the lingual side, the loss reaches approximately one-third of the original bone height. Additionally, it has been observed that tooth tilt causes greater bone resorption than axial displacement. The extent of this tilt corresponds to the amount of resorption, but no direct correlation was found. This may be related to the fact that other factors, such as gingival phenotype or individual periodontal conditions, may influence the biological response resulting from orthodontic movement and make it impossible to find any mathematical correlation [18].

Mao et al. performed a retrospective cohort study, the results of which confirmed that because of orthodontic movement involving the retraction of the incisors, there is a significant reduction in bone thickness on the palatal side, and the displacement of the incisor tips is the main factor that determines the size of this change [19]. This confirms that while the alveolar process can undergo dynamic remodeling in growing patients, orthodontic movement in adults must be limited by the orthodontic walls of the cortical plates [27].

The most recent included studies as incorporated by Wang et al. confirmed significant atrophy of the palatine bone at all levels; however, no changes in the thickness of the process on the labial side were observed. These studies additionally showed that after almost two years of retention at the L1 level, there is an increase in bone volume on the lingual side, while no significant changes occur in other areas [20].

The above studies demonstrate that significant bone loss occurs on the palatal side because of incisor retraction. This amount may depend on both the extent of the incisor shift and the change in their inclination, and thus, the change in the position of the root tips. This change is significantly higher in adults than in growing adolescents. Cellular functions decline with age, which may explain the reduced ability to remodel as we age. Additionally, the rate of retraction may result in greater bone loss since repair processes may not keep up with resorption processes [20]. However, bone changes on the labial side are debatable. Further research is necessary, which would make the obtained measurements dependent on other factors, such as, perhaps, the speed and biomechanics of retraction, the applied orthodontic force, or the age of the patients.

The latest research conducted by Guo et al. may be optimistic, suggesting that despite the frequent occurrence of bone dehiscence on both the palatal and labial sides after orthodontic treatment using incisor retraction, the situation improves during retention by initiating bone remodeling. Additionally, spontaneous reorientation of the incisor roots was observed, which contributes to covering the fenestration and dehiscence with a thin layer of bone. In addition, the thick gingiva covering the palatal bone may enable bone tissue regeneration by preserving periodontal ligaments, which participate in bone remodeling. [28]

It should, therefore, be assumed that orthodontic movement in adults takes place through the bone, and most often, the bone does not adapt to the new position of the teeth. The palatal cortical lamina should be treated as an intact wall that limits the range of planned movement of the incisors. An additional limitation is the lamina compacta, which surrounds the incisive canal and may be the first to get in the way of the incisors during retraction and may also cause their resorption [23,24]. Advanced incisor protrusion should be treated as early as possible in the adolescent growth period when the body's ability to remodel is high and when orthodontic movement occurs together with the bone. At this age, the incisive canal, the inclination of which is dependent on the inclination of the incisors, may also have a greater capacity for remodeling [23,24].

5. Conclusions

The studies show that because of incisor retraction, there is a statistically significant change in bone thickness. Significant bone loss is noted on the palatal side. This observed change may depend on both the extent of the incisor shift and the change in their inclination, and, thus, the change in the position of the root tips. This change is significantly higher in adults than in growing adolescents. Cellular functions decline with age, which may explain the reduced ability to remodel as we age. Additionally, the rate of retraction may result in greater bone loss since repair processes may not keep pace with resorption processes. The changes in the bones on the labial side are controversial, as they show both gains and losses. Further research is necessary to make the obtained measurements dependent on other factors, such as the speed and biomechanics of retraction, orthodontic force magnitude, and patient age.

6. Limitations

The primary constraints of this review encompass the inclusion of articles published exclusively in English within the last 10 years. This may affect the risk of statistical publication bias. Additionally, only studies that relied on 3D CBCT imaging were included.

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8.5. Publikacja 5

materials

MDPI

Article

The Hydrostatic Pressure Distribution in the Periodontal Ligament and the Risk of Root Resorption—A Finite Element Method (FEM) Study on the Nonlinear Innovative Model

Anna Ewa Kuc [1,*], Kamil Sybilski [2], Jacek Kotuła [1], Grzegorz Piątkowski [3], Beata Kowala [1], Joanna Lis [1], Szymon Saternus [2] and Michał Sarul [4]

[1] Department of Dentofacial Orthopedics and Orthodontics, Wroclaw Medical University, 50-425 Wroclaw, Poland; j_kotula@poczta.onet.pl (J.K.); beata.kawala@umw.edu.pl (B.K.); joanna.lis@umed.wroc.pl (J.L.)
[2] Faculty of Mechanical Engineering, Military University of Technology, 00-908 Warsaw, Poland; szymon.saternus@wat.edu.pl (S.S.)
[3] Greg Dent Orthodontics Sp. Z O.O., 91-163 Lodz, Poland; grzegorz.piatkowski@greg-dent.pl
[4] Department of Integrated Dentistry, Wroclaw Medical University, 50-425 Wroclaw, Poland; michal.sarul@umw.edu.pl
* Correspondence: annaewakuc@wp.pl

Abstract: Excessive orthodontic force can induce inflammatory tooth root resorption due to sustained high stresses within the periodontal ligament (PDL). This study aimed to analyze the PDL pressures during upper incisor retraction using the en masse method with TISAD. The finite element method (FEM) ensured consistent conditions across cases. The models included bone geometry, adjacent teeth, PDL, and orthodontic hardware, analyzed with LS-Dyna. The pressure ranged from 0.37 to 2.5 kPa across the dental arch, with the central incisors bearing 55% of the load. The pressure distribution remained consistent regardless of the force or hook height. The critical pressure (4.7 kPa) was exceeded at 600–650 g force, with notable pressure (3.88 kPa) on the palatal root wall of the right central incisor. Utilizing 0.017 × 0.025 SS archwires in MBT 0.018 brackets provided good torque control and reduced the root resorption risk when forces of 180–200 g per side were applied, maintaining light to moderate stress. Triple forces may initiate resorption, highlighting the importance of nonlinear finite element analysis (FEA) for accurate oral cavity simulations.

Keywords: PDL hydrostatic pressure; root resorption; orthodontic treatment; FEM; incisor retraction; en masse retraction; PDL stress distribution

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1. Introduction

Orthodontic treatment employing sliding biomechanics represents the prevailing method for restoring proper occlusion. In instances of crowding, Class II malocclusion, incisor protrusion, or when preparing for surgical correction of Class III defects, extraction of the upper first premolars is frequently indicated to facilitate incisor retraction. Alternatively, in less severe cases, distalization of the entire dental arch may be warranted to restore proper occlusion and enhance the patient's facial profile [1]. In clinical practice, orthodontists have a choice between two types of bracket slots: 0.018 and 0.022 inches. The selection of an appropriate steel archwire size depends on the chosen slot, through which the desired orthodontic movements are executed. Factors such as the archwire dimensions, hook height, and torque play a crucial role in controlling incisor inclination during arch retraction or distalization. The archwire's stiffness aids in preventing unwanted inclinations and the occurrence of a "roller coaster" effect, which can exacerbate vertical overjet. Furthermore, in cases of significant severity, orthodontic mini-implants serve as valuable skeletal anchors, offering superior torque and anchorage control [2,3].

The integration of brackets, archwires, force vectors, and orthodontic techniques, in conjunction with the anatomy of the maxillary alveolar process, dictates orthodontic movement and potential side effects such as excessive incisor tipping, contact with the lamina dura, or root resorption, particularly in the upper incisors. The primary objective of orthodontic treatment is to attain optimal tooth displacement while minimizing adverse effects and enhancing the patient's facial profile.

Orthodontic movement is facilitated by the inherent ability of the alveolar processes in the maxilla and mandible to undergo remodeling in response to orthodontic forces. Adhering to the principles of homeostasis governing bone apposition mediated by osteoblasts and bone resorption regulated by osteoclasts is vital for facilitating optimal bone remodeling, resulting in the formation of healthy bone tissue. The cyclical processes of resorption and apposition inherent in orthodontic interventions should be carefully managed in accordance with biomechanical principles to promote the development of healthy, well-structured bone throughout the entire therapeutic process. However, in pathological conditions, such as pathological osteolysis, inflammation plays a pivotal role in initiating and perpetuating bone destruction. Excessive activation of inflammasome–supramolecular protein complexes responsible for maturing and secreting pro-inflammatory cytokines can lead to chronic inflammation, infection spread, and uncontrolled alveolar bone loss, potentially occurring during orthodontic treatment [4].

The activation of inflammasomes may contribute to alveolar bone loss in response to orthodontic force application. This process closely correlates with the induction of periodontal inflammation. Moreover, increased orthodontic force can enhance the pro-osteoclastogenesis capacity of osteoblasts while simultaneously diminishing osteoblast activity, thereby reducing the bone formation ability, differentiation, and proliferation, and promoting osteoblast pyroptosis. Consequently, this dysregulation results in unchecked bone resorption and compromised new bone formation [5].

The application of orthodontic force generates stresses within the periodontal ligament (PDL), which, when surpassing the blood pressure in the capillary arterioles, induce hyalinization, ischemia, and necrosis of adjacent tissues, root cement, and alveolar bone. Cells near the necrotic area may initiate root resorption [6]. Hence, a correlation has been established between excessive orthodontic force, resulting in sustained high stress levels in the PDL, compromised blood flow, and orthodontically induced inflammatory tooth root resorption (OIIRR) [7].

However, the precise origins of orthodontically induced inflammatory tooth root resorption (OIIRR) remain incompletely elucidated. Its etiology is notably multifaceted and not entirely comprehended. Apart from the aforementioned excessive orthodontic forces, the various contributing factors include genetic predisposition, duration of orthodontic treatment, extent of tooth displacement, and the nature of the force applied, whether continuous or intermittent [8–13]. Additionally, root resorption may occur due to contact with the lamina dura related to the alveolar process or the incisive canal [9,14–16]. Notably, Kaley and Philips demonstrated a twentyfold increase in the risk of root resorption of the upper incisors due to cortical plate contact [9]. Hence, meticulous torque control and personalized planning of incisor positioning within the existing bone envelope are imperative for preserving healthy roots.

Measuring the pressure values within the periodontal ligament (PDL) resulting from orthodontic treatment and their distribution in the roots is impractical under clinical conditions. However, such values can be estimated through the finite element method (FEM) model analysis pioneered by Yettram et al. in orthodontics [17]. This method enables the simulation of complex mechanical stress scenarios within the jaw, alveolar ridge, and teeth. By analyzing the results, it becomes possible to identify the loads and locations where pressures may exceed those in the periodontal blood vessels, potentially leading to complications such as root resorption.

Finite element analysis (FEA) stands out as an exemplary approach for scrutinizing data within mathematical models. It furnishes precise, accurate, and quantifiable insights, enabling thorough evaluation and analysis across various strata. Consequently, FEA emerges as the quintessential analytical tool for assessing the stress and strain in implantology's planned technical systems. A key characteristic of the finite element method (FEM) is its high fidelity in replicating physical properties between the real-world structure and the FEM model. However, it warrants acknowledgment that oversimplification of the geometry of the object under scrutiny poses a potential risk of yielding inconsistent evaluation outcomes [18].

Objective

The objective of this study was to analyze the pressure exerted on the periodontium of tooth roots during the retraction of upper incisors using the en masse method with Temporary Anchorage Devices (TADs) following the extraction of first premolars using a high-standard innovative finite element model. Additionally, this study aimed to assess the pressure during the retraction of the entire dental arch, considering the applied force and its vector on the 0.017 × 0.025 stainless steel (SS) archwire in 0.018 MBT prescription slot brackets, utilizing finite element model analysis.

2. Materials and Methods

To achieve the objectives, a research methodology centered on numerical analyses, specifically employing the finite element method, was chosen. This approach facilitated the precise replication of conditions across all cases under examination. Ensuring the uniformity of conditions is essential for meaningful comparative analysis of selected parameters.

2.1. Construction of a Numerical Model

One of the primary objectives of this study was to faithfully replicate real patient conditions while ensuring the proper consideration of cranial stiffness in the preservation of dental and periodontal structures. To achieve this, a numerical model was constructed based on computed tomography (CT) scans of the cranial region and intraoral scanning. DICOM files derived from the CT scans were processed into STL files utilizing the MIMICS system (Materialise, Leuven, Belgium) [19]. During this process, emphasis was placed on delineating three distinct geometrical groups: compact bone, spongy bone, and teeth (inclusive of their roots). To enhance the geometric precision, each layer of the DICOM file was meticulously outlined based on grayscale values corresponding to individual structures.

The result of this process was a surface mesh consisting of triangles representing the outer contour of the cortical bone (Figure 1a) and teeth (Figure 1b). The cancellous bone was delineated by identifying the enclosed volumes within the cortical bone contour.

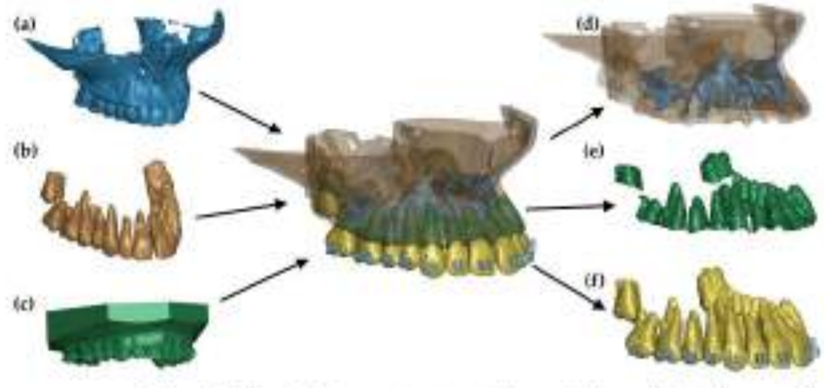


Figure 1. FE model: (**a**) geometry extracted from a CT image, (**b**) teeth extracted from a CT image, (**c**) scan of a dental arch with brackets, (**d**) combination of cortical and cancellous bone, (**e**) finite elements of the periodontium, and (**f**) teeth with brackets.

In addition, data from intraoral scans of dental arches, including those with fixed brackets, were included in the construction of the numerical model. The dental arch scan (Figure 1c) was aligned with the teeth delineated from the CT scans, and then STL models of the brackets provided by the manufacturer were imported and individually positioned for each tooth.

In the subsequent phase, the contours delineating the cortical bone, cancellous bone, teeth, and brackets (see Figure 1d) were populated with a mesh of 3D elements using the Hypermesh system (Altair, Troy, MI, USA). Tetragonal elements were selected for this purpose. Taking advantage of the tooth and bone geometries, the periodontal ligament (PDL) was modeled using hexahedral elements, with an assumed consistent thickness of 0.25 mm [20]. The average mesh size was set to 0.32 mm.

The final stage of replicating the patient's anatomy was to model the mini-implant and wire. The wire was shaped based on the bracket geometry, delineating a rectangular cross-section along a curve connecting successive bracket openings. Hexahedral elements were used to reproduce this geometry in the numerical model. Consequently, a comprehensive numerical model comprising 3D elements was generated, as depicted in Figures 2–4.

Figure 2. Cross-section: numerical model.

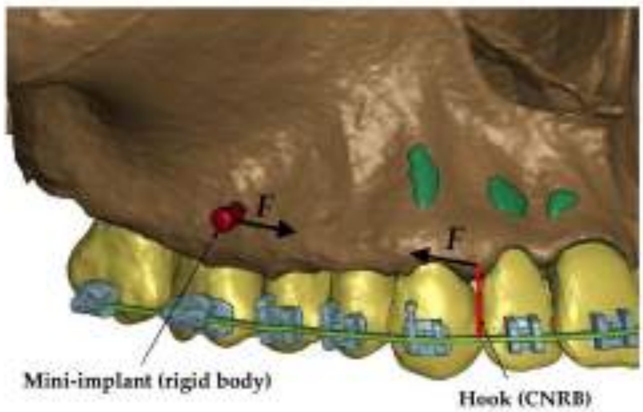


Figure 3. Load representation in the numerical model.

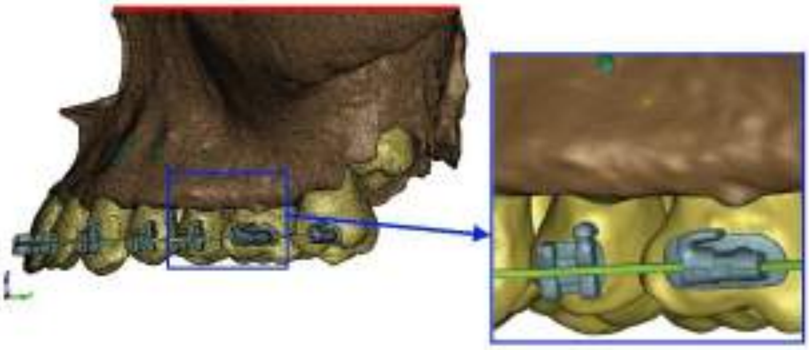


Figure 4. Boundary condition in the numerical model (red line represents constrained surface) and finite elements (average mesh size ≈ 0.32 mm).

2.2. Material Modeling

In the numerical model, based on the preliminary simulations, it was verified that the wire, brackets, teeth, and bones would be subjected to low loads and that there would be no significant stresses in these components. It was therefore assumed that these structures would be modeled using an isotropic, linear elastic constitutive model. The brackets and wire were made of steel. The material data for the above components are given in Table 1.

Table 1. Material data used to describe the material behavior.

Component	Young's Modulus [MPa]	Poisson's Ratio
Steel	210,000	0.30
Tooth [21]	18,600	0.31
Cortical bone [22]	13,700	0.30
Cancellous [22]	2000	0.30

The most heavily loaded component, and at the same time, the component of greatest interest to the authors, was the periodontium (PDL). Therefore, the hyperelastic Ogden model was used to model the PDL. This model assumes that the behaviour of the material can be described by the strain energy function, from which the stress–strain relationship can be derived. In the Ogden model, the strain energy function is defined by the function:

$$W = \sum_{i=1}^{3} \sum_{j=1}^{n} \frac{\mu_j}{\alpha_j}(\lambda_i^{\alpha}j - 1) + K(J - 1 - \ln J) \tag{1}$$

where W is the strain energy potential, λ_i is the main deviant stretches, μ_i and α_i are material parameters, J is the determinant of the elastic strain gradient, and K is the volume modulus. The bulk modulus is calculated using the values of Poisson's ratio and Young's Modulus. The parameters presented in Table 2 [23] were used to describe the behavior of the PDL.

Table 2. Parameters used for describing the PDL.

μ_1 [MPa]	α_1 [MPa]	Poisson's Ratio
2.5×10^{-3}	150	0.46

2.3. Restraint and Load Conditions, Contacts

In the developed numerical model, the mini-implant's stiffness significantly surpassed that of the surrounding structure. Consequently, the mini-implant (see Figure 3) was represented as a rigid element constrained to the adjacent nodes. Similarly, a hook attached to the wire was modeled using the same approach. The rigid element, called a Constrained Nodal Rigid Body (CNRB), encompasses all six degrees of freedom. In practical scenarios, an elastic element typically bridges the gap between the mini-implant and the hook, generating tension of a predetermined magnitude. Thus, within the numerical model, a coordinate system was established with the x-axis aligned between the CNRB nodes, corresponding to the actual positions of the fixtures. Along this defined x-axis, a force (F) was applied, as illustrated in Figure 3. The force was therefore applied between the upper node of the hook (Figure 3) and the outer node of the mini-implant. This procedure was replicated on both sides of the numerical model.

The numerical model was fixed over the entire surface of the upper part (Figure 4—red color). All the translational degrees of freedom of the nodes lying on this surface have been fixed.

Appropriate contacts were defined between the touching components. A penalty function-based contact with a friction coefficient of 0.6 was defined between the wire and the brackets [24]. The tooth brackets were attached using a tied contact available in the LS-Dyna system. The same contact was defined between the teeth and periodontium, periodontium and bone. All the analyses were static and were performed using an implicit integration step in the LS-Dyna system. The individual loads changed linearly during the analysis from 0 at t = 0 to the maximum value at t = 1.

3. Results

The hydrostatic pressure values σ_h, along with the distribution map within the periodontal ligament (PDL) during en masse retraction using Temporary Skeletal Anchorage Devices (TISADs) subsequent to the extraction of first premolars in the 0.018 slot on the 0.017 × 0.025 stainless steel (SS) arch, employing various hook heights and force magnitudes, are presented in Tables 3–6. Table 3 depicts the comprehensive distribution and pressure values σ_h across the entire dental arch. Furthermore, Table 4 delineates the pressure σ_h distribution and values within the PDL of the roots of the upper central incisors, while Table 5 elucidates the corresponding data for the upper lateral incisors. Additionally, Table 6 portrays the distribution and pressure σ_h values within the PDL of the canine roots.

Across a force spectrum ranging from 50 g to 300 g, the pressure σ_h values for the entire dental arch vary between 0.37 kPa and 2.5 kPa (see Table 3). Notably, the pressure σ_h values demonstrate a linear correlation with the increment of applied force (refer to Figure 5). However, marginal differences are observed in the pressure values σ_h corresponding to different hook heights for a given force magnitude, which are clinically insignificant. Notably, in all the described scenarios, the lowest pressure σ_h is observed for a 6 mm hook height, while the highest is noted for a 2 mm hook height.

The pressure σ_h exerted within the periodontium of the central incisors (refer to Table 4) spans from 0.23 kPa to 1.54 kPa, exhibiting a linear relationship with the applied force. In contrast to the entire dental arch, the minimum pressure σ_h values are observed at the lowest hook height of 2 mm, progressively escalating with an increased hook height. Across all instances, the pressure σ_h values exerted on the central incisors represent approximately 55% of the total pressure values observed within the periodontium of the entire dental arch.

The pressure σ_h in the periodontium of the lateral incisors (Table 5) is approximately 45% of the pressure of the full arch and ranges from 0.18 kPa to 1.14 kPa, with a linear distribution. Unlike the entire arch and central incisors, the lowest values are recorded at the highest hook height of 10 mm and increase as the hook height decreases.

In the case of the canines (Table 6), the pressure values σ_h are the highest and constitute approximately 75% of the value of the entire pressure in the PDL of a full arch. The values range from 0.28 to 1.83 kPa. The relationships are equivalent for the lateral incisors.

Table 3. Pressure σ_h [kPa] distribution in the PDL—entire dental arch.

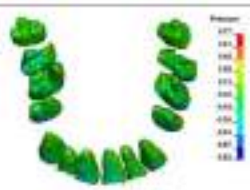
50 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
100 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 3. *Cont.*

150 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
200 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 3. *Cont.*

300 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

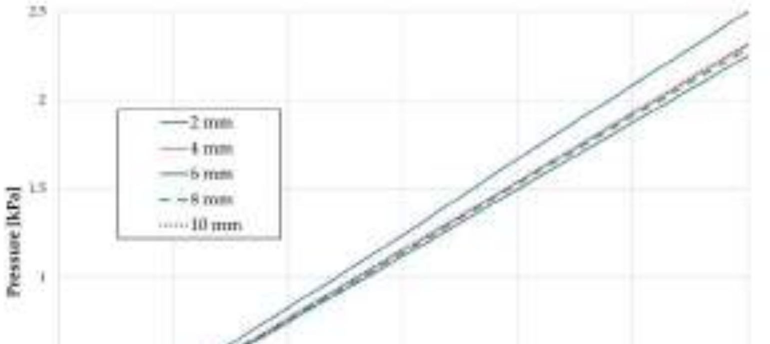


Figure 5. Pressure σ_h versus load applied in the PDL for the entire dental arch.

Table 4. Pressure σ_h [kPa] distribution in the PDL—central incisors.

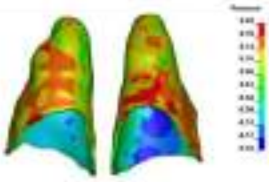
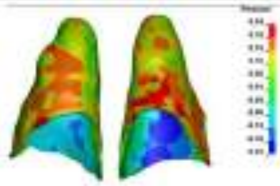
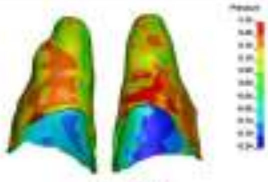
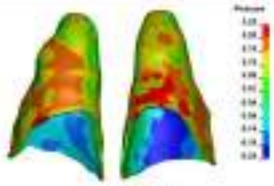
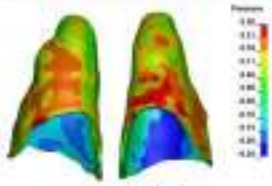
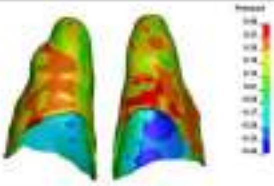
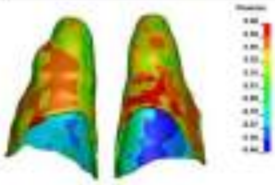
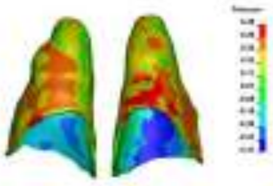
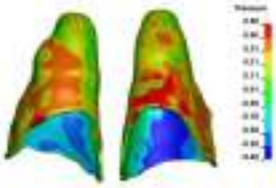
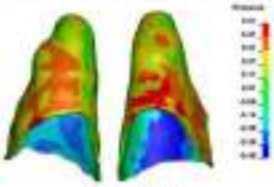
50 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
100 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 4. *Cont.*

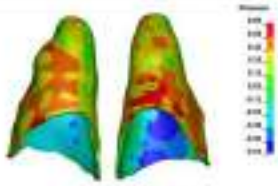
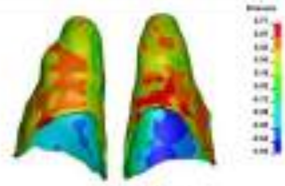
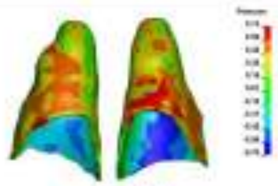
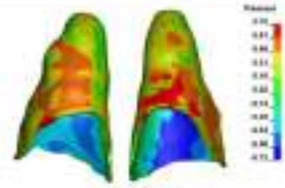
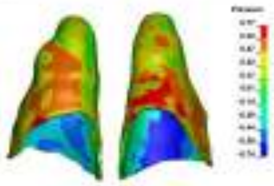
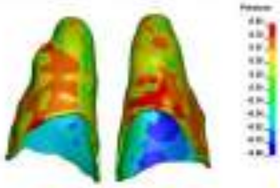
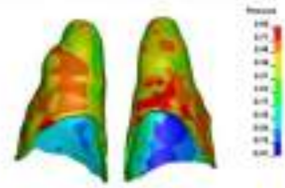
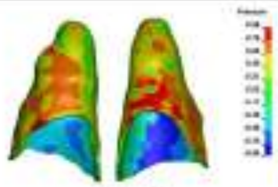
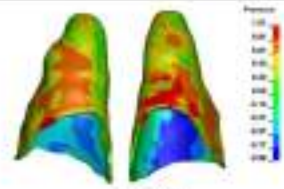
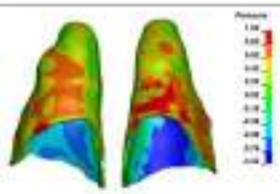
150 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
200 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 4. *Cont.*

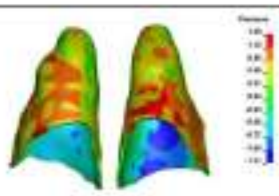
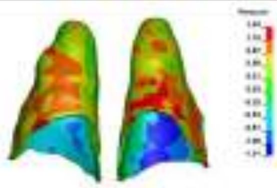
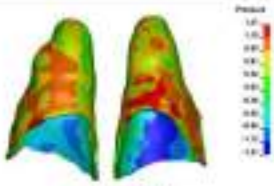
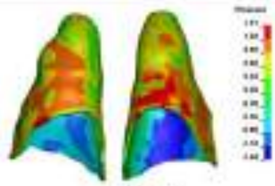
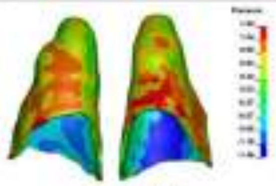
300 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 5. Pressure σ_h [kPa] distribution in the PDL—lateral incisors.

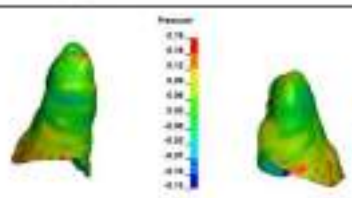
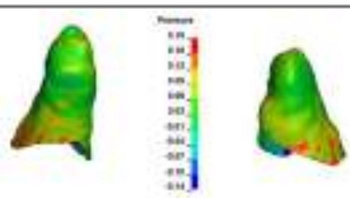
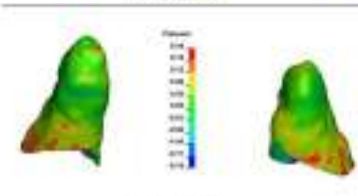
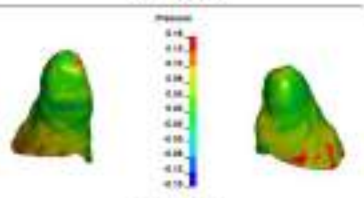
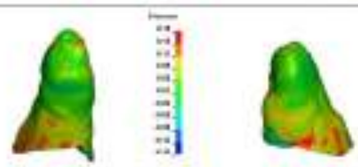
50 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 5. *Cont.*

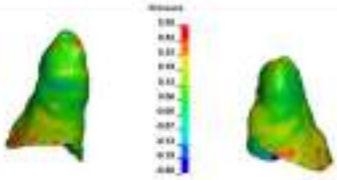
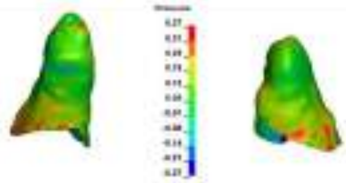
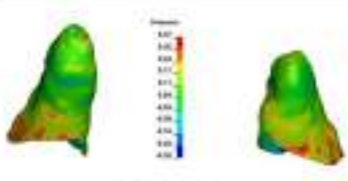
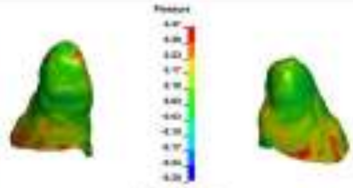
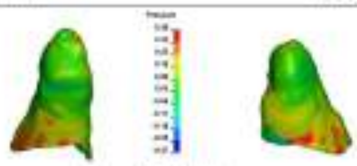
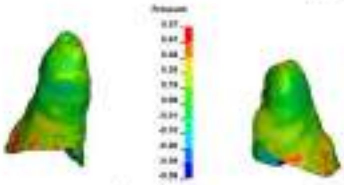
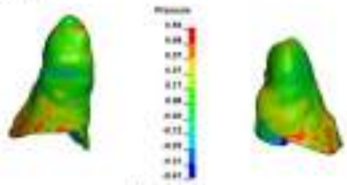
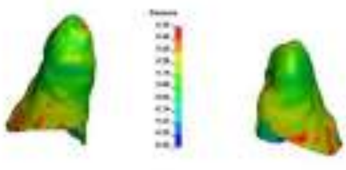
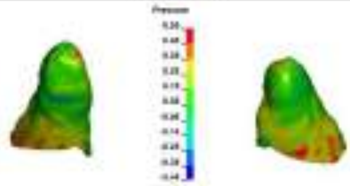
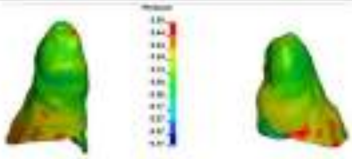
100 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
150 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 5. *Cont.*

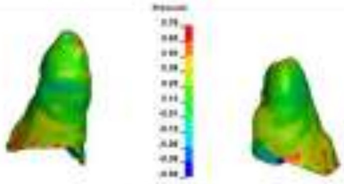
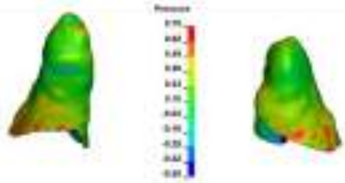
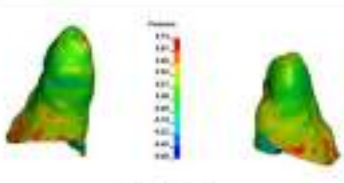
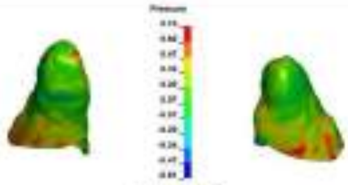
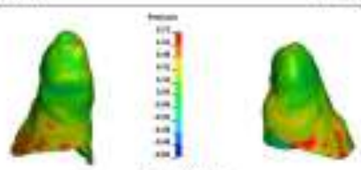
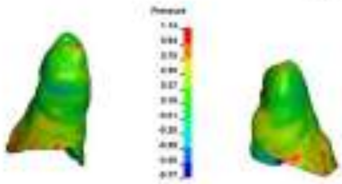
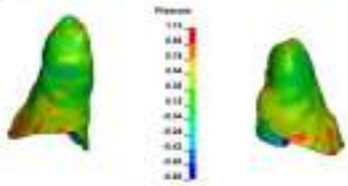
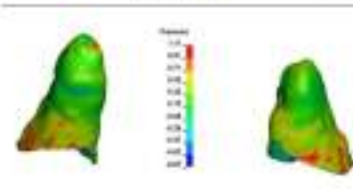
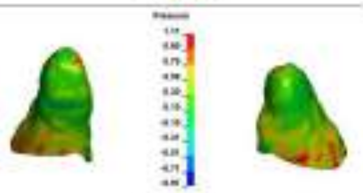
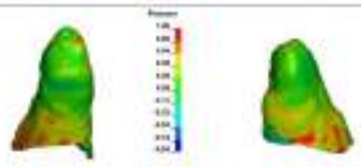
200 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
300 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 6. Pressure σ_h [kPa] distribution in the PDL—canines.

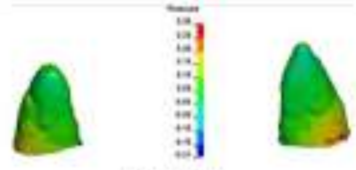
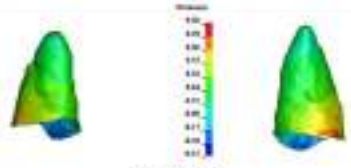
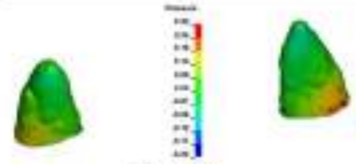
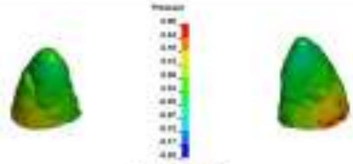
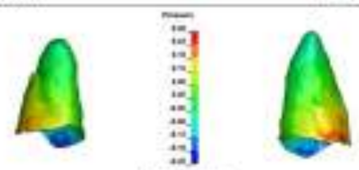
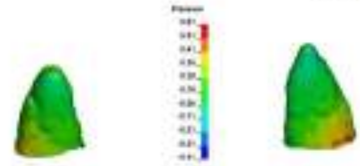
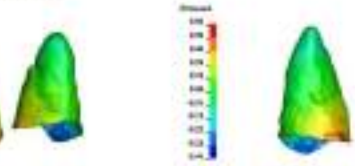
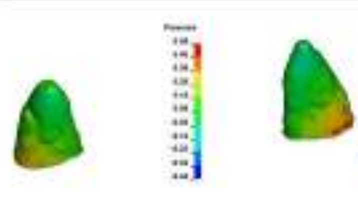
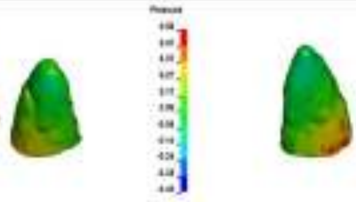
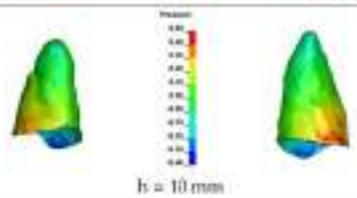
50 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
100 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 6. *Cont.*

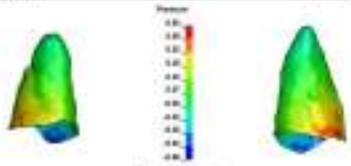
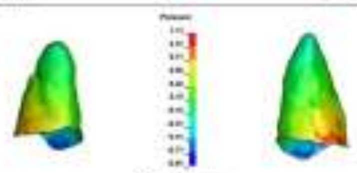
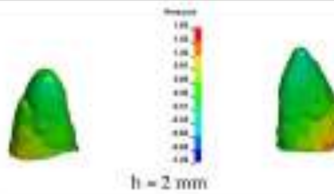
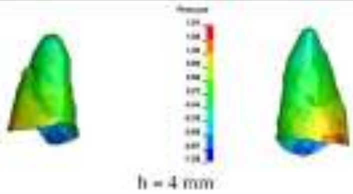
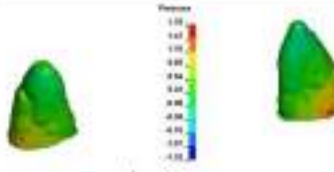
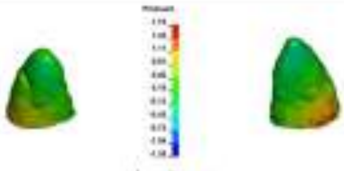
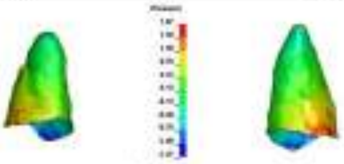
	 h = 2 mm h = 4 mm
150 g	 h = 6 mm h = 8 mm
	 h = 10 mm
	 h = 2 mm h = 4 mm
200 g	 h = 6 mm h = 8 mm
	 h = 10 mm

Table 6. *Cont.*

300 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

During the comparative analysis of the hydrostatic pressure σ_h within the periodontal ligament (PDL) across both the entire dental arch and individual teeth, the distribution map remains consistent irrespective of the applied force or hook height. Therefore, the distribution map remains constant regardless of the force vector utilized, with only the proportional values varying (refer to Tables 3–6).

For the central incisors, the highest pressure σ_h values are observed along the palatal aspect, with consistent accumulation predominantly in the lower half across all cases. Additionally, the apical third of the roots typically resides within the neutral pressure zone, except for minor points at the apices where higher pressures concentrate. Notably, higher pressure σ_h values are generally observed for the right incisor compared to the left incisor (see Table 3).

Regarding the lateral incisors, pressure σ_h accumulation predominantly occurs in the cervical region along the distal palatal wall and at specific points near the apices, while the remaining portions of the roots reside within the neutral pressure zone (refer to Table 5).

However, the majority of the canines are located in the neutral zone, with a single place of pressure σ_h accumulation in the cervical area of the palatal wall. The left canine has slightly higher values (Table 6).

The critical value of 4.7 kPa is exceeded for the full dental arch with a force of 642 g and is concentrated on the upper roots of the first molars, reaching at the same time in the anterior segment 2.93 kPa, which accumulates mainly on the right central incisor in the area of the lower palatal half root walls (Figures 6 and 7).

The pressure σ_h values, along with the distribution map generated within the periodontal ligament (PDL) during distalization of the entire dental arch using Temporary Skeletal Anchorage Devices (TISADs) in the 0.018 slot on the 0.017 × 0.025 stainless steel (SS) arch employing various hook heights and force magnitudes, are delineated in Tables 7–10. Table 7 presents the comprehensive distribution and pressure σ_h values across the entire dental arch. Furthermore, Table 8 depicts the pressure distribution and values within the PDL for the roots of the upper central incisors, while Table 9 elucidates the corresponding data for the upper lateral incisors. Additionally, Table 10 portrays the distribution and pressure σ_h values within the PDL for the roots of the canines and first premolars.

In the range of applied forces from 50 g to 300 g, the pressure σ_h values for the entire dental arch are very similar and range from 0.33 kPa to 2.4 kPa (Table 7). The pressure σ_h values also increase linearly with the increase in the applied force (Figure 8). However, the differences at the level of one force value at different hook heights are even more minimal. All the dependencies are as above. The pressure σ_h values are approximately 9–10% lower everywhere. However, the pressure σ_h distribution map is the same in all cases.

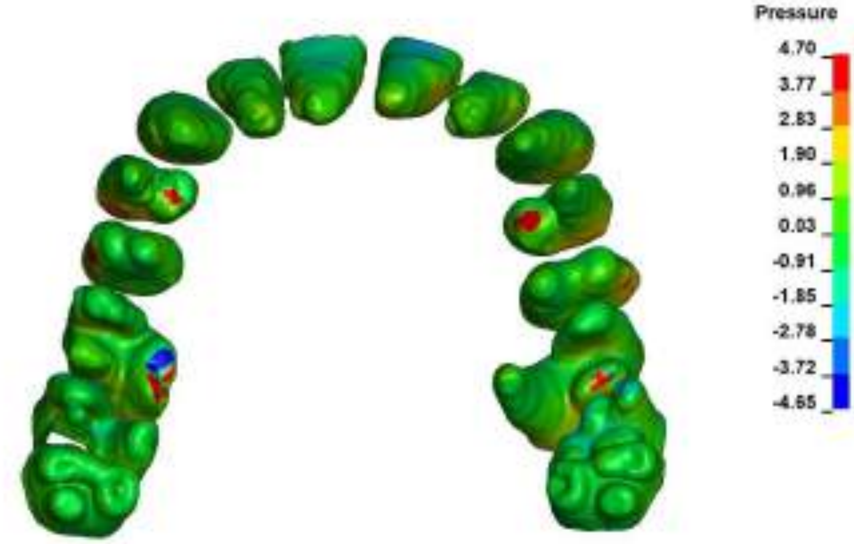


Figure 6. Pressure σ_h [kPa] in the PDL for load = 642 g—full arch.

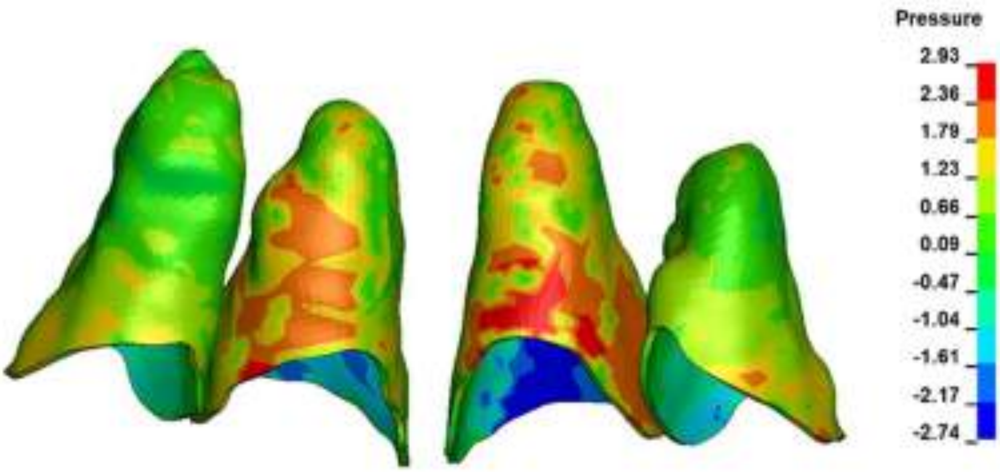


Figure 7. Pressure σ_h [kPa] in the PDL for load = 642 g—central incisors.

Table 7. Pressure σ_{h} [kPa] distribution in the PDL—entire dental arch.

50 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
100 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 7. *Cont.*

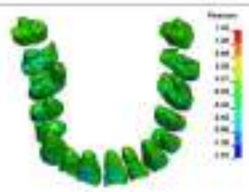
150 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
200 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 7. *Cont.*

300 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

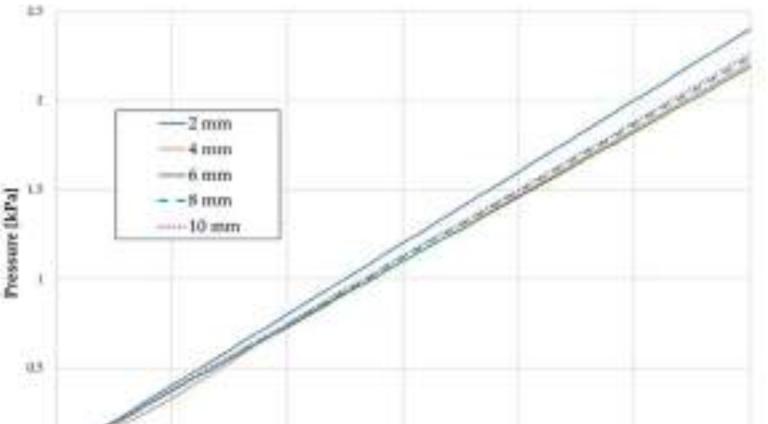


Figure 8. Pressure σ_h [kPa] versus load applied in the PDL for the entire dental arch.

Table 8. Pressure σ_h [kPa] distribution in the PDL—central incisors.

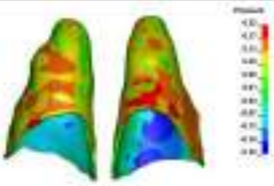
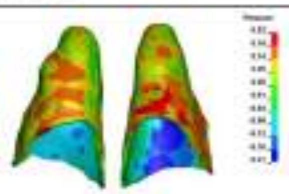
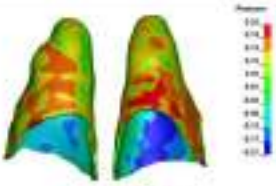
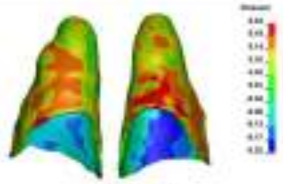
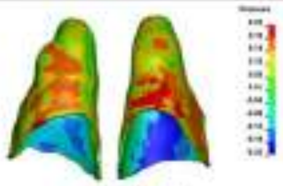
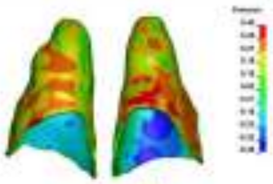
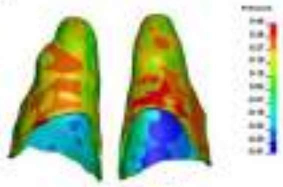
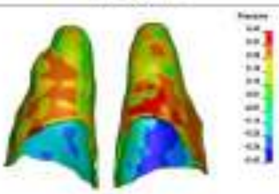
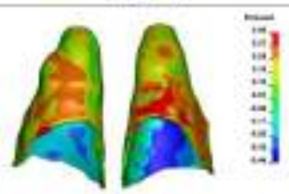
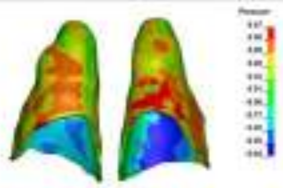
50 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
100 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 8. *Cont.*

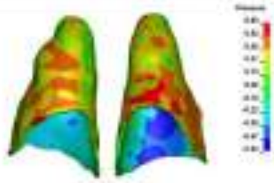
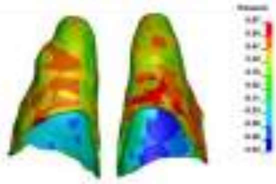
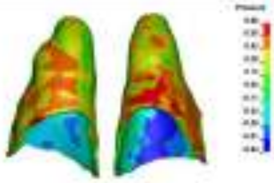
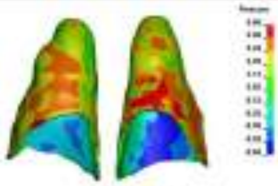
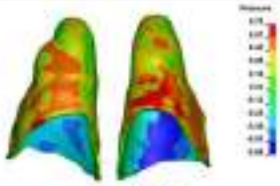
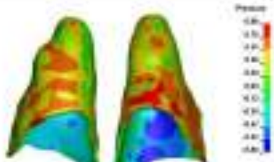
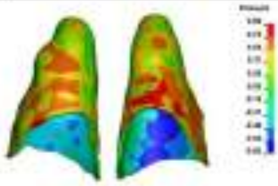
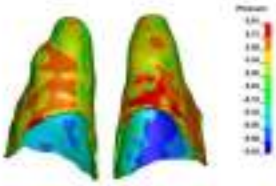
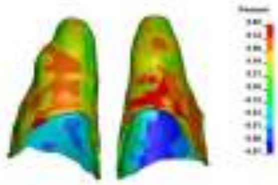
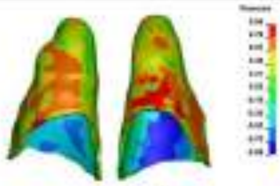
150 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
200 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 8. Cont.

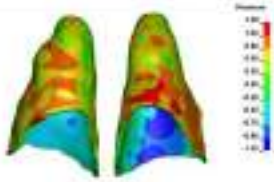
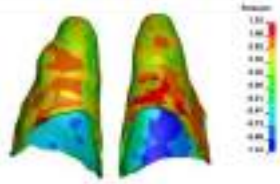
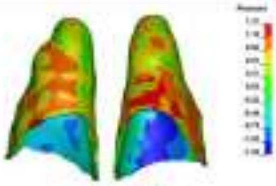
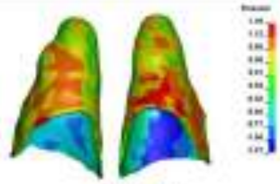
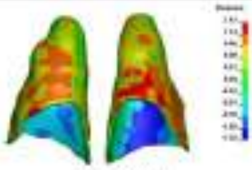
300 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 9. Pressure σ_h [kPa] distribution in the PDL—lateral incisors.

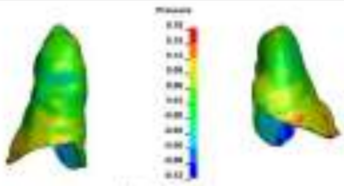
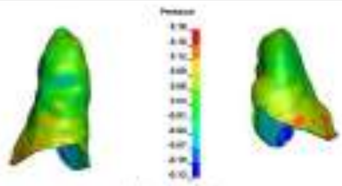
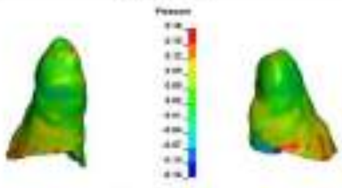
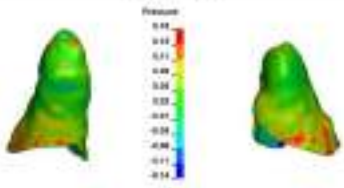
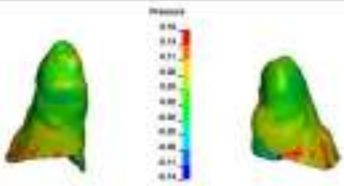
50 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 9. *Cont.*

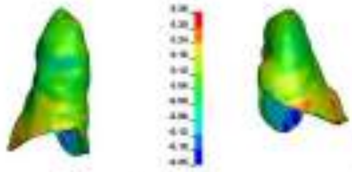
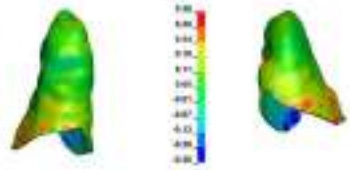
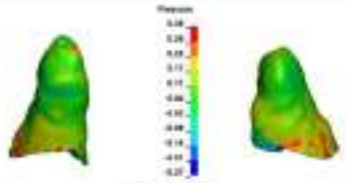
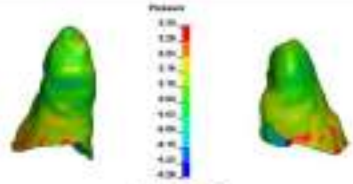
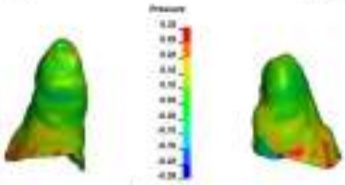
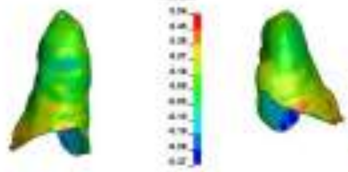
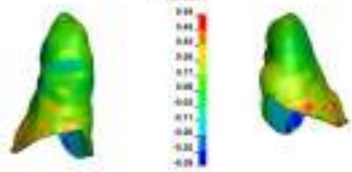
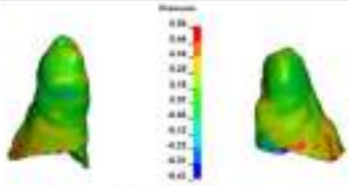
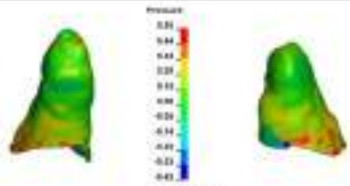
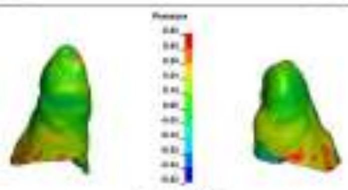
100 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
150 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 9. *Cont.*

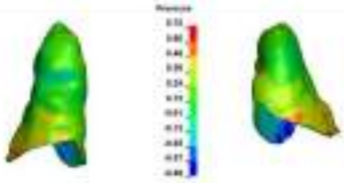
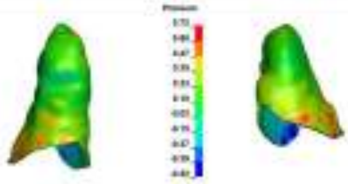
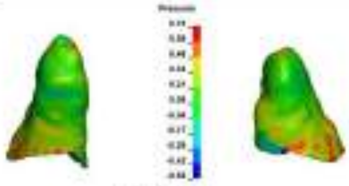
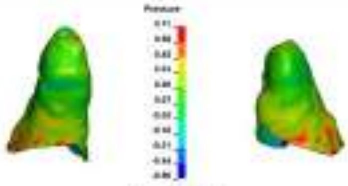
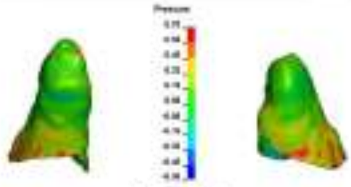
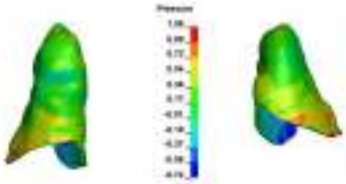
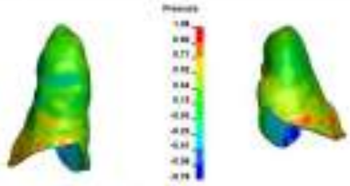
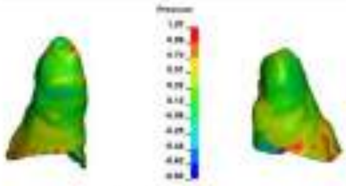
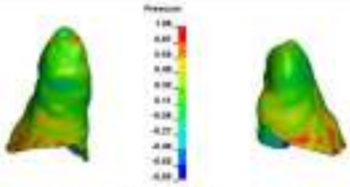
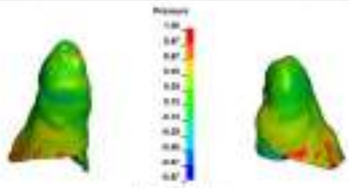
	 h = 2 mm	 h = 4 mm
200 g	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
	 h = 2 mm	 h = 4 mm
300 g	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 10. Pressure σ_1, [kPa] distribution in the PDL—canines.

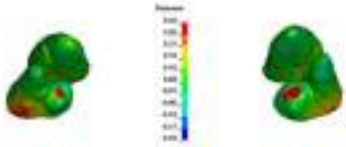
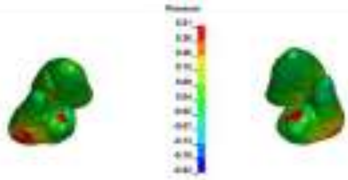
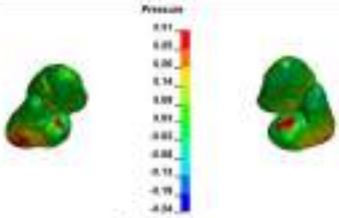
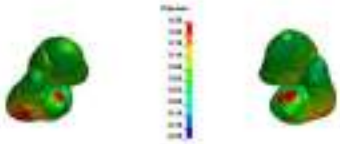
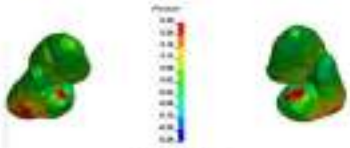
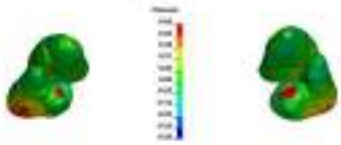
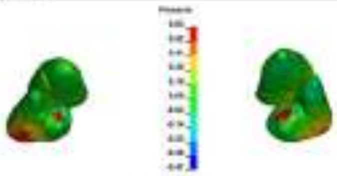
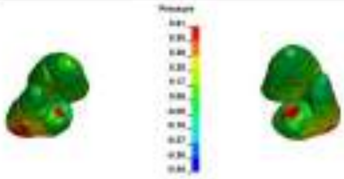
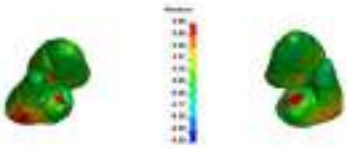
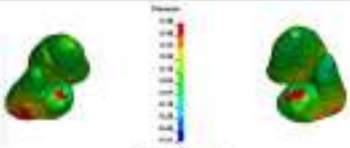
50 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
100 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 10. *Cont.*

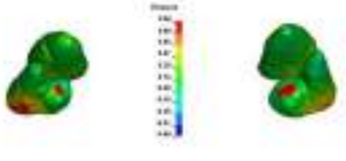
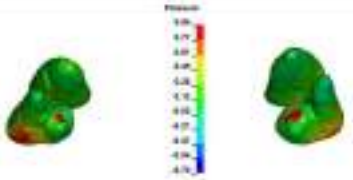
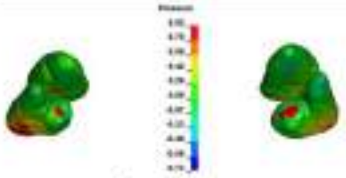
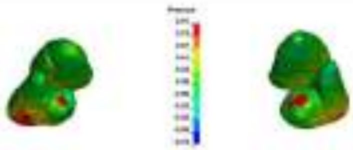
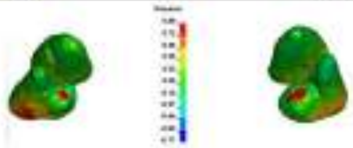
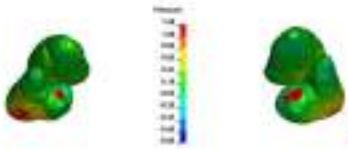
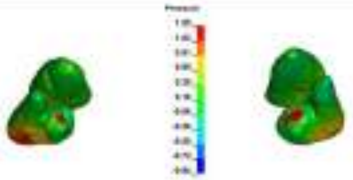
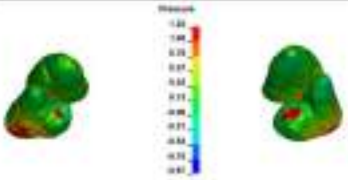
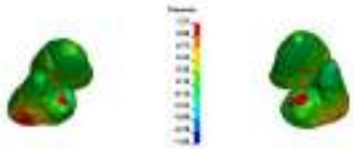
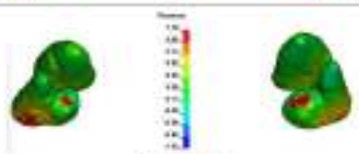
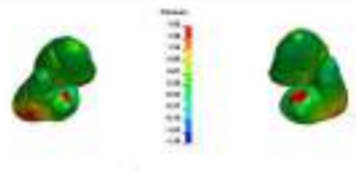
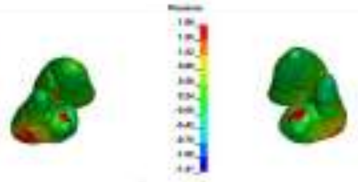
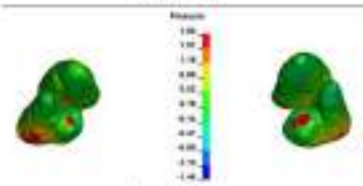
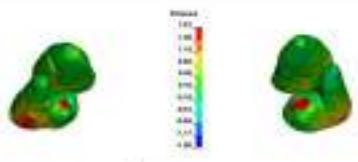
150 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	
200 g	 h = 2 mm	 h = 4 mm
	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

Table 10. *Cont.*

	 h = 2 mm	 h = 4 mm
300 g	 h = 6 mm	 h = 8 mm
	 h = 10 mm	

4. Discussion

Side effects are common occurrences during orthodontic treatment, with root resorption (OIRR) being a frequent concern. The initial signs of resorption typically become evident under a microscope approximately two weeks after treatment initiation [25], while radiological manifestations may appear several months into treatment [26,27]. Although previous studies suggest that the bracket size and archwire selection do not significantly influence the occurrence of resorption [28,29], contact with the cortical lamina is a well-documented risk factor for severe root resorption [9].

The most desirable outcome of orthodontic treatment is achieving axial movement of the teeth while maintaining appropriate torque control to minimize the risk of root tip movement in the opposite direction. Often, achieving this goal necessitates additional interventions such as bilateral corticotomy, intrusion archwires or skeletal anchorage. This is particularly important due to the approximately 9–10% difference in torque between the working archwires, such as 0.0190.025 stainless steel wires in 0.022 brackets, and the commonly used archwires, such as 0.0160.022 wires in brackets with a 0.018 slot [30].

The finite element model (FEM) represents a modern and invaluable tool for assessing the risk of root resorption associated with necrosis induced by capillary lumen closure due to stress and increased pressure σ_h within the periodontal ligament (PDL) resulting from orthodontic force application. The reliability of this method varies based on the quality of the model preparation. One of the salient characteristics of FEM is the near physical similarity among the real structure as well as its FEM. However, unnecessary simplification of geometry will invariably lead to inconsistent results [18]. Linear models, which have been the focus of much research [31–40], lack specificity and fail to accurately represent bodily tissues compared to nonlinear models [8]. In our proposed research, we utilized a high-quality, innovative, fully flexible nonlinear model based on Cone Beam Computed Tomography (CBCT) scans of a typical patient with Class II/1 mal-occlusion requiring extensive retraction. This model includes comprehensive anatomy, encompassing the vestibular and palatal cortical plates, alveolar laminae, interdental septa, and the incisive canal lamina, with all the structures interacting as they would in vivo. By ensuring all the stresses are accurately transmitted to the surrounding structures, we can confidently assume the high reliability of our measurements. The presence of fenestrations in the vestibular plate of the maxillary alveolar process, subsequent to tooth movement for alignment and insertion of a 0.017 × 0.025 stainless steel (SS) working wire into orthodontic brackets, serves as a clear indication of the consequences of inappropriate orthodontic treatment methods. Failure to respect the bone envelope and reduce tooth material while expanding the dental arch can lead to such complications.

The periodontal ligament (PDL) plays a crucial role in orthodontic movement [41]. Therefore, the model should accurately represent the movement of teeth through the periodontium and various bone layers with appropriate elastic moduli, ensuring interconnectedness. In our analysis, we focused on hydrostatic stress σ_h rather than von Mises stress σ_{vM} and minimum principal stress σ_3, as the former is directly associated with the formation of resorption lacunae in tooth roots [8,37]. Research has demonstrated that locations where the hydrostatic pressure σ_h exceeds 4.7 kPa correspond to areas of root resorption observed via electron microscopy. Conversely, areas exhibiting expansion during model simulation did not exhibit active resorption [31]. Clinical studies have not revealed resorption defects in locations with high von Mises σ_{vM} values or minimum principal stress σ_3 as determined by finite element analysis [8].

This study focused on analysing 0.018-inch slot brackets. It demonstrated a linear relationship between the applied force and the resulting pressure σ_h in the periodontal ligament (PDL) of tooth roots, with increasing force leading to higher hydrostatic pressure σ_h. These findings align with previous studies by Owman-Moll [42] and Maltha [43] but contradict those of Cas [44] and Chan and Darendeliler [45]. This study also explored the percentage distribution of pressure among different tooth groups: 55% on the central incisors, 45% on the lateral incisors, and 75% on the canines. Notably, this distribution has not been reported in the prior literature. Furthermore, no significant differences were observed in the hydrostatic pressure σ_h values or their distribution maps concerning the height of the hook, whether during en masse retraction or the distalization of the entire arch. These findings are particularly intriguing, as one might expect significant changes in the movement mechanics when extracting teeth. However, our study revealed that during en masse retraction with appropriately low forces, the distribution of stresses σ_h around the roots of the anterior teeth remains largely unchanged. It is worth noting that due to our utilization of newer modeling techniques, comparisons with studies using linear models, measuring von Mises stresses σ_{vM} or minimum principal stress σ_3 [31,34,35,46–48], or examining PDL deformation [48] are challenging.

The absence of significant high values at the incisor apices and the relatively even distribution of the roots along the palatal wall suggest effective torque control and axial displacement of the teeth, irrespective of the applied force vector. These conclusions differ from those of Tominaga et al., whose study revealed discrepancies in the axial displacement among the front teeth segment at a hook height of 5 mm positioned behind the lateral incisor, as well as tilting at hook heights of 0 mm and 10 mm [49,50]. Such variations may stem from the utilization of an individualized model that accurately reflects the anatomical conditions under which specific biomechanics are employed and all stresses are transferred to adjacent structures. Additionally, in the presented model, the applied force may result in the bending of both the root and the interdental septum plate, which may result in a different stress σ_h distribution than in simplified models. Further research is warranted to confirm or refute this hypothesis.

Based on the study findings, it can be inferred that a threefold increase in the optimal orthodontic force for en masse retraction, ideally ranging from 180 to 200 g per side, leads to areas where the pressure σ_h within the periodontal ligament (PDL) exceeds 4.7 kPa. This poses a significant risk of root resorption due to the complete occlusion of capillaries, leading to root necrosis and subsequent resorption [37]. It is conceivable that during a two-stage retraction of a segment comprising four incisors, a force less than three times the applied value may still result in capillary occlusion, as the force is distributed over a smaller number of teeth. However, further research is necessary to conclusively validate this hypothesis.

Upon analysis of the above results, it becomes evident that meticulous control of the forces and torques acting on the incisor roots during torque control is paramount in preventing tooth root tip resorption. In our model, even under axial movement, substantial forces are evenly distributed across the surface, locally remaining below the critical value σ_h of 4.7 kPa. Optimal orthodontic forces, ranging from 180 to 200 g per side, result in pressure σh values slightly exceeding half of the critical threshold. This level of pressure may stimulate physiological bone resorption, facilitating orthodontic movement without adverse effects by modulating blood flow in the capillaries without complete occlusion. The present study reveals that lateral incisors experience heightened pressure solely in the cervical area, remaining free from significant hydrostatic stresses σ_h on both the palatal and labial aspects. However, despite this, resorption of the four upper incisors is a common occurrence in clinical practice. Nevertheless, based on our findings, it can be inferred that such occurrences are less probable when utilizing a 0.017 × 0.025 archwire in a 0.018 slot with the force values specified by the authors. In this scenario, there is no abrupt increase in hydrostatic pressure σ_h in the apical region, which could initiate the formation of resorption defects. These results are applicable to both en masse retraction treatment following premolar extraction and during full arch distalization.

Brackets featuring a 0.018 slot were replaced in the initial phase of treatment due to their inadequate size, which is undesirable when creating ample clearance in the brackets. Additionally, their use led to increased friction during the sliding mechanics and insufficient space between the working arch and the bracket slot. Nevertheless, recent studies indicate that these brackets offer excellent torque control. Moreover, the inconvenience associated with their use in the initial alignment phase may be mitigated in the current era of high-quality, thin 0.014 A-NiTi archwires. These brackets and archwires possess significant potential to minimize the severe root resorption attributed to ischemia and excessive tipping, thereby reducing the likelihood of unintentional contact with the cortical lamina, particularly the vestibular lamina.

In their randomized studies comparing the effectiveness and treatment quality of both 0.018 and 0.022 brackets, Yassir et al. observed no significant differences in treatment outcomes [51]. Therefore, considering the hydrostatic pressure σ_h distribution described above, it may be reasonable to regard these brackets as viable alternatives to mitigate the risk of root resorption, particularly in individuals with thin ridges and other root resorption risk factors where precise torque control is essential. It can also be taken into account that resorption during orthodontic treatment may be caused by nickel–titanium wires or rectangular wires, which may have enhanced energy exceeding the threshold values [52]. Over the last few years, research has focused on clear aligners and no research has been conducted on the problem we are analyzing. Other previous studies concerned a similar method but on different sized arches, which makes comparison impossible. In the research conducted by Ruenpol on the en masse retraction of the upper anterior tooth segment in 0.018 slot brackets on thinner 0.016 × 0.022 SS arches, the greatest stresses were found in the central part of the roots, while the greatest expansions were found in the apical third of the maxillary lateral incisors [48]. In his research, Taminaga noticed that the axial displacement of teeth does not occur when force is applied at the level of the center of resistance. His analysis showed that in the 0.018 × 0.025 SS wire, the translational movement takes place at a level of 2.2 mm lower than the resistance center toward the incisal edge, while in the 0.016 × 0.022 arc, it is 3.8 mm higher than the resistance center toward the apex [50]. This does not agree with our results, in which the 0.018 slot on 0.017 × 0.025 SS showed good torque control regardless of the amount of applied force. In turn, Singh's research in 0.022 slot brackets on 0.019 × 0.025 SS wire showed that the stress value in the cortical bone around the central and lateral incisors increases linearly with the increase in the height of the hook. Additionally, the authors noticed high stress values around the canines and associated that with the fact that they are surrounded mainly by cortical bone. They also showed that as the height of the hook increases, the stresses decrease at the canines and increase at the incisors [47]. Our results indicate that the new type of modeling may provide different results in terms of the application and point of application of the optimal force. Moreover, the use of our tooth retraction parameters means that the force value has a large tolerance range before it exceeds the optimum and also provides excellent torque control.

5. Conclusions

1. Optimally, 0.017 × 0.025 SS archwires in MBT 0.018 brackets provide excellent torque control, leading to precise axial displacement of the teeth.
2. When applying optimal forces of 180–200 g/side, there is no risk of root tip resorption due to the even distribution of light and medium hydrostatic pressure σ_h in the periodontal ligament (PDL).
3. The application of triple orthodontic forces (600–640 g/side) can initiate the resorption process by occluding the capillaries.
4. Attempting to level the dental arch with a significant dentoalveolar discrepancy may result in fenestrations of the vestibular plate of the alveolar process.
5. High-quality nonlinear models for finite element analysis (FES) are recommended to ensure reliable, comparable, and realistic simulations closely resembling the oral cavity conditions.

Limitations

The presented model assumes passive insertion of the wire into the brackets after full leveling.

Author Contributions: A.E.K., M.S. and K.S. were the authors of the research concept; A.E.K., K.S., S.S. and M.S. collected the data and were the main co-authors in terms of writing the manuscript. A.E.K., K.S., J.K., M.S., J.L. and B.K. analyzed and interpreted the data. A.E.K., K.S., J.K., G.P. and M.S. were responsible for preparing the tables and references. All authors have read and agreed to the published version of the manuscript.

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8.6. Publikacja 6

Journal of
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Systematic Review

The Assessment of the Rank of Torque Control during Incisor Retraction and Its Impact on the Resorption of Maxillary Central Incisor Roots According to Incisive Canal Anatomy—Systematic Review

Anna Ewa Kuc [1,*], Jacek Kotula [1], Jakub Nawrocki [2], Alicja Babczyńska [1], Joanna Lis [1], Beata Kawala [1] and Michał Sarul [3]

1 Department of Dentofacial Orthopedics and Orthodontics, Wroclaw Medical University, Krakowska 26, 50-425 Wroclaw, Poland
2 Dental Star Specialist Aesthetic Dentistry Center, 15-215 Białystok, Poland
3 Department of Integrated Dentistry, Wroclaw Medical University, 50-425 Wroclaw, Poland
* Correspondence: annaewakuc@wp.pl

Abstract: Background: Root resorption is one of the complications of orthodontic treatment, and has a varied and unclear aetiology. Objective: To evaluate the relationship between upper incisor resorption and contact with the incisive canal and the risk of resorption during orthodontic treatment associated with upper incisor retraction and torque control. Search methods: According to PRISMA guidelines, the main research question was defined in PICO. Scientific databases MEDLINE, EMBASE and the Cochrane Central Register of Controlled Trials were searched for linking keywords: Resorption of roots incisive canal, Resorption of roots nasopalatine canal, Incisive canal retraction and Nasopalatine canal retraction. Selection criteria: No time filters were applied due to the significantly limited number of studies. Publications in the English language were selected. Based on the information provided in the abstracts, articles were selected according to the following criteria: controlled clinical prospective trials and case reports. No randomised clinical trials (RCTs) or controlled clinical prospective trials (CCTs) were found. Articles unrelated to the topic of the planned study were excluded. The literature was reviewed, and the following journals were searched: American Journal of Orthodontics and Dentofacial Orthopedics, International Orthodontics, Journal of Clinical Orthodontics, Angle Orthodontist, Progress in Orthodontics, Orthodontics and Craniofacial Research, Journal of Orofacial Orthopedics, European Journal of Orthodontics and Korean Journal of Orthodontics. Data collection and analysis: The articles were subjected to risk of bias and quality assessment using the ROBINS-I tool. Results: Four articles with a total of 164 participants were selected. In all studies, differences in root length were observed after contact with the incisive canal, which was statistically significant. Conclusions and implications: The contact of incisor roots with the incisive canal increases the risk of resorption of these roots. IC anatomy should be considered in orthodontic diagnosis using 3D imaging. The risk of resorption complications can be reduced by appropriate planning of the movement and extent of the incisor roots (torque control) and the possible use of incisor brackets with built-in greater angulation. Registration CRD42022354125.

Keywords: resorption; incisive canal; nasopalatine canal; retraction

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1. Introduction

Planning orthodontic treatment often involves the extraction of the first premolars. In malocclusions associated with protrusion and in cases of high skeletal discrepancy, maximum incisor retraction is often necessary to improve not only occlusion, lip position and the patient's facial and smile profile, but also periodontium protection [1–3]. The introduction of orthodontic mini-implants as a maximum anchorage has enabled much more effective treatment and greater tooth displacement. However, the limit of maximum incisor retraction has been debatable for years. The accepted standard, according to the envelope of discrepancy established by Proffitt and Ackerman in 1994, is the possibility of the retraction of the upper incisors by approximately 7 mm [4]. The determination of these dimensions was based on 2D radiographs and the presence of the cortical plate. In the era of widespread availability of CBCT examination with the possibility of using TISAD, the anatomy of each patient can be carefully and individually analysed, with retraction in excess of 7 mm being a possibility for application [5]. The use of retraction is characterised by longer treatment times, the use of greater forces and tooth movement over a greater distance compared to other types of treatment. The above characteristics may be the causes of orthodontically induced inflammatory root resorption (OIIRR) [6–15]. Tooth root resorption during orthodontic treatment is one of the most common iatrogenic complications [6]. Many factors contribute to this phenomenon. In recent years, as a result of the development of 3D imaging, attention has been drawn to another important element, namely the incisive canal, and its relationship to upper incisor roots. The incisive canal, also known as the nasopalatine canal, is the connection between the nasal cavity and the oral cavity, containing vessels and nerves within it. It is an often overlooked element in the orthodontic treatment planning process, but it is surrounded by a relatively thick cortical plate. As there is evidence of an effect of the buccal and palatal cortical plate on the induction of root resorption [6,16,17], the cortical plate of the incisive canal could be an analogous factor. In this systematic review, the authors attempted to gather evidence on the relationship between resorption and the presence and anatomy of the incisive canal, as well as the circumstances under which the canal collides with roots, and also to assess the risk in individual patient groups during orthodontic treatment and the role of incisor torque control depending on growth direction, skeletal class, gender or treatment with or without incisor retraction.

Objective

The aim of the study was to analyse the possibility of minimizing the resorption of incisor roots during retraction through appropriate treatment planning and control of their inclination in relation to the individual anatomy of the incisive canal.

2. Materials and Methods

2.1. Protocol and Registration

The systematic review was registered in the PROSPERO database under the identification number CRD42022354125. The study was conducted in accordance with PRISMA guidelines [18]. Due to the type of the study, there was no patient participation, no intervention, and no requirement to collect any personal data, hence ethical approval was not requested.

2.2. Eligibility Criteria

The study design was defined in PICO format: Population (P)—patients with complete permanent dentition; Intervention (I)—orthodontic extraction treatment with braces using a straight wire technique with incisor retraction; Comparison (C)—assessment of the distance between the upper incisor roots and the canal before and after treatment and assessment of the length of the incisor roots before and after treatment; Outcome (O)—statistically significant/non-significant differences in the distance between the upper incisor roots and the canal before and after treatment and in the length of the incisor roots before and after treatment.

Due to the significantly limited number of studies, randomised clinical trials (RCTs), controlled clinical prospective trials (CCTs), systematic reviews, retrospective studies and case reports were included. Only publications in the English language were selected.

2.3. Information Sources and Search Strategy

The authors (A.E.K., J.K. and J.N.) conducted an independent search of the following electronic databases: PubMed, EMBASE and the Cochrane Central Register of Controlled Trials, Web of Science, Scopus, by entering the following keywords:

- Root resorption incisive canal;
- Root resorption nasopalatine canal;
- Incisive canal retraction;
- Nasopalatine canal retraction.

The literature was reviewed, and the following journals were manually searched: American Journal of Orthodontics and Dentofacial Orthopedics, International Orthodontics, Journal of Clinical Orthodontics, Angle Orthodontist, Progress in Orthodontics, Orthodontics and Craniofacial Research, Journal of Orofacial Orthopedics, European Journal of Orthodontics and Korean Journal of Orthodontics. Handsearching was performed by screening similar articles under every article found by keywords. No time filters or status were applied. All the databases were searched from 14 July 2022 to 31 July 2022. Grey literature sources were screened, such as Pro-Quest Dissertations and Theses Global and Google scholar. If data from the study reports were insufficient, unclear, or missing, we attempted to contact the study authors for additional information. If we judged that the missing data might render the result uninterpretable, we excluded the data from the analysis and clearly stated the reason.

2.4. Study Selection

The authors (A.E.K., J.K. and J.N.) independently searched databases and, after duplicate removal, reviewed titles by their relevance to the topic of this systematic review. Articles included after title screening were evaluated thoroughly. Due to the limited number of on-topic studies, no exclusion criteria were applied. The reviewers were blinded to each other's decisions. The authors discussed any disagreements until a consensus was reached, and if necessary the fourth author (MS) was consulted.

2.5. Data Collection and Data Items

The following data were extracted to Microsoft Excel: sample size, year of publication, author's name, mean amount of root resorption after intervention, difference between mean root resorption in control and retraction group, standard deviation for listed data, general characteristics of each group, general characteristics about intervention associated with each group. Study investigators (authors of the articles accepted in the systematic review) would be contacted for unreported data or additional details.

2.6. Risk of Bias in Individual Studies

In accordance with the Cochrane Handbook for Systematic Reviews of Interventions, the Risk of Bias (RoB) was achieved using Risk of Bias In Non-randomized Studies of Interventions (ROBINS-I tool) [19]. It was planned to use the Cochrane risk-of-bias tool (RoB 2) for randomized trials; however, due to the absence of RCTs, using the RoB 2 tool was unnecessary. An overall judgement about the risk of bias was reached after completing 7 main domains for each study. The outcome of overall bias could be: 1. low risk of bias, 2. moderate risk of bias, 3. serious risk of bias, 4. critical risk of bias, 5. no information. The evaluation was performed by 2 authors (A.E.K. and J.N.) independently. The authors discussed any disagreements until a consensus was reached, and if necessary the last author (MS) was consulted.

2.7. Summary Measures, Synthesis of Results and Additional Analyses

The planned formal method of combining individual study data, randomised and controlled clinical studies was statistically evaluated both jointly (by heterogeneity analysis—the Cochrane Q test and I^2 statistics, and random-effect meta-analysis) and separately (statistical importance between groups in each study) with subgroup analysis and significance established at $p < 0.05$. Results of the analyses will be presented graphically with forest plots after comparisons of study designs, methodologies and participants, to judge the clinical heterogeneity of the studies. Unfortunately, due to the lack of RCTs and CCTs and an inability to test the heterogeneity of the studies, this prevents the conducting of statistical analysis and meta-analysis.

3. Results

The keywords yielded 1862 abstracts. Thirty-nine articles were initially validated as eligible for the systematic review, and they were analysed in detail. In the end, six articles were selected, including four controlled clinical prospective trials and two case reports. The full selection process is shown in Figure 1.

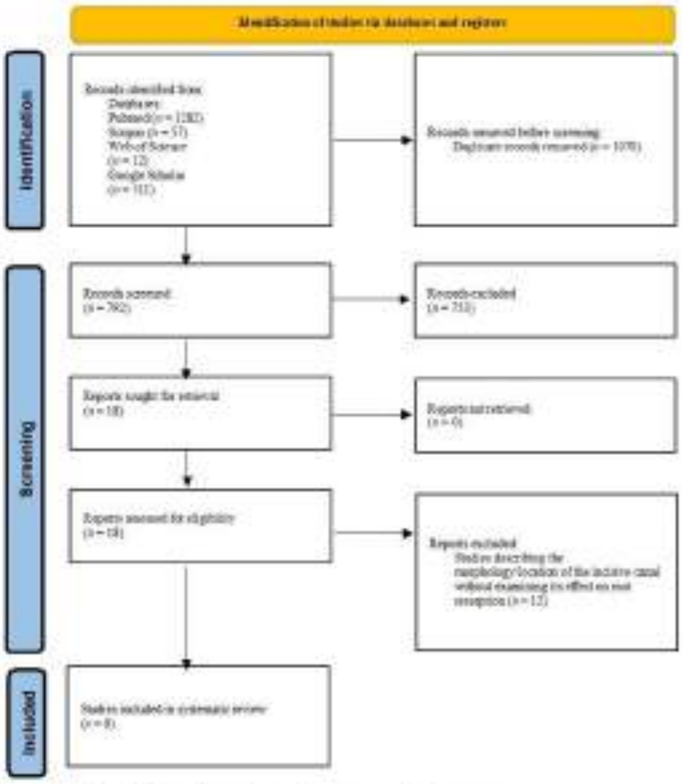

Figure 1. PRISMA flow diagram of the literature selection process.

3.1. *Group Population*

The total number of participants was 164. The average group population was 33 patients. The largest group was found in the articles by Yu et al. [1], with 35 participants in the group. The smallest group was included in the study by Nakada et al. [20], with 30 participants. Only one study included a control and a retraction group [18]; in the remaining studies, only retraction groups were present (Table 1).

Table 1. Studies Included in the Systematic Review.

Reference	Patients	Groups	Age (Years ± SD)	Patients Malocclusion	Treatment Method	Assessment Method	Results
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Pre- and post-treatment CBCT	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	n/a	[illegible]	Pre- and post-treatment CBCT	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Pre- and post-treatment CBCT	Root Length Decrease [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Pre- and post-treatment CBCT and panoramic radiograph	Patient 1 "severe apical root resorption"
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Pre- and post-treatment CBCT	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Pre- and post-treatment CBCT	[illegible]

Abbreviations: F, female; M, male; G0, group 0; G1, group 1; G2, group 2; G3, group 3; ANB, angle formed by point A, nasion (N) and point B; CBCT, cone beam computed tomography; n/a, not applicable.

3.2. Age and Gender

In most studies, participants were adult patients; in the study by Pan et al. [2], participants were also adolescents. In each study, the female group population was larger than the male group population; see Table 1.

3.3. Treatment Strategy

In treated patients, extractions of maxillary premolars were performed to gain space for incisor and canine retraction. In two studies, maximum anchorage in the form of TISAD was applied to the study groups. In the remaining two groups, there was no information on the use of TISAD (Table 1).

3.4. Risk Analysis

The main parameters were a change in the length of the incisor roots before and after treatment and the distance between the roots and the incisive canal before and after treatment.

In all studies, a relationship was observed between the resorption of the upper incisor roots and their proximity to the incisive canal.

In all studies, the root resorption of the central upper incisors occurred during incisor retraction. The greatest resorption was observed in the study by Chung, in a group with canal invasion and without remodelling 3.3 ± 1.54 mm (Table 1).

3.5. Changes in the Length of the Central Incisor Roots in Contact with the Incisive Canal

In all articles, the shortening of the upper incisor roots after retraction was statistically greater when contact was made with the incisive canal. The results of statistically significant studies are presented below (Table 1).

Yu et al. [1] revealed a greater root resorption in the retraction group (2.3 ± 1.40 mm) compared to the control group (1.1 ± 0.75 mm). In addition, subgroups were created according to the distance from the roots to the IC after treatment (separation, approximation, contact, invasion). The closer the incisor root was to the incisive canal, the greater the resorption, but this result was not statistically significant. The retraction group was four times more likely to have root invasion or contact with the incisive canal compared to the control group. In 11.4 percent of the retraction group, there was a change in the course of the incisive canal, which may point to its remodelling ability.

Chung et al. [3] found that 53 percent of retraction treatment cases resulted in the invasion of the incisive canal by the incisor roots. A higher risk of contact between the roots and canal was shown when the inter-root distance was less than the width of the incisive canal. In the subgroup with invasion, resorption was statistically higher (2.4 ± 1.59 mm) than in the non-invasive group (0.8 ± 0.96 mm) $p < 0.0001$. Resorption was lower in patients with invasion and remodelling (1 ± 0.92 mm) compared to patients without remodelling (3.3 ± 1.54 mm) $p < 0.0001$.

Pan et al. [2] showed a significantly greater shortening (2.63 ± 0.93) of the incisor roots in the contact group between the roots and the incisive canal than in the group without contact (1.14 ± 0.83), possibly pointing to their positive correlation. With uncontrolled tipping of the incisors, there is an increased risk of canal invasion in the cervical area. The risk of root contact is increased when the position of the incisive canal is low.

Nakada et al. [20] showed that root resorption was statistically greater on the side closer to the incisive canal than on the opposite side. In addition, the range of palatal resorption on the side closer (2.49 ± 0.61) to the canal was also greater than on the farther side (1.51 ± 0.49 mm). Ultimately, he concluded that the proximity of the apex to the IC cortical plate was a factor in root resorption.

Imamura et al. [22] described a clinical case of a patient in whom, after the retraction of the incisors, the root of the one in contact with the incisive canal resorbed at the contact area (3.6 mm). Therefore, the size and morphology of the IC was considered to have an impact on root resorption.

Chung et al. [21] also described a case of root resorption after contact with the IC, together with tooth vitality preservation.

3.6. Risk of Bias

The risk of bias analysed according to the ROBINS-I tool (Figure 2) can be described as critical for all articles but one—Nakada et al. [20], where the risk of bias was serious. Despite the critical and serious overall risk of bias, the studies may be accepted as useful. Only one domain categorized studies at high or critical risk, and it was caused by the nature of the research. In the study by Pan et al., retraction was performed using TISAD (maximum anchorage), but there is no information on whether the placement of the mini-implants was the same in all cases and thus whether the force vector followed a similar course. The researchers statistically analysed the retraction distance and the difference in incisor inclination before and after retraction, but did not tabulate specific values. Similarly, there was no information on the type of brackets or whether each patient was treated with the same prescription. In the study by Yu et al., the extent of retraction (determinant of group membership—<2 mm control, >4 mm retraction) was given, but there was no information on the method of treatment other than that the retraction group involved premolar extraction. In addition, there was no information about torque control during treatment and no information about the type of brackets and whether each patient in the control and retraction groups was treated in the same way. The study by Nakada et al. only considered one group out of all those studied—only in this group could there be an association between the presence of the incisive canal and root resorption. There was no information about the method of treatment, extent of retraction or torque control; only information on the distance by which the central incisors were moved was provided. The small sample size is also a factor of error. The best-matched study group was represented by the study by Chung et al. [3]. It reported the average treatment time, and the patients qualified for the study met certain conditions: Skeletal Class I or II malocclusion, bimaxillary protrusion, treatment completed with Class I canine relationship and retraction >4 mm. Study group exclusion criteria were investigated and TISAD was used, but there was no information on its location or type of brackets, torque control or retraction distance (the only information was >4 mm).

Figure 2. The results of the bias risk assessment according to the ROBINS-I tool [1–3,20].

3.7. Analysis of Results

The planning of orthodontic treatment of malocclusions associated with bimaxillary protrusion and a skeletal Class 2 malocclusion with incisor protrusion often involves premolar tooth extraction to make room for maximum incisor retraction. Orthodontic mini-implants, which have been in use for many years, enable maximum anchorage and a range of retraction that can exceed the patient's anatomical conditions. Often, 7 mm in the maxilla, as determined by Profitt and Ackerman, is given as the maximum retraction range based on the palatal cortical plate, which is a limiting factor [4,23]. The studies analysed by the authors on the change in the incisor root length after contact with the incisive canal and the sheer diversity of the morphology of the incisive canal in terms of possible contact with the incisor roots show that this range may be smaller in some patients because it is located between the roots of the incisor teeth and the palatal cortical plate, and may be the first to stand in the way of the displaced maxillary incisors. As is common knowledge, the incisive canal, also known as the nasopalatine canal, is an anatomical structure located in the midline protecting the incisive nerve and blood vessels [24,25]. The introduction of CBCT imaging enabled a more accurate diagnosis and analysis of anatomical structures in the field of orthodontic displacement, with these images providing more complete information compared to panoramic radiography and lateral cephalometric radiography [25]. There are few studies or publications on the possible relationship between canal morphology and proximity to incisor roots in terms of orthodontic treatment complications. However, the current publications included in this systematic review clearly indicate a possible higher risk of resorption of the incisor roots during retraction and lateral displacement or intrusion after contact with the cortical plate of the incisive canal [1–3,20]. These studies are characterised by moderate evidential value due to the nature of controlled clinical prospective trials. Among these, Chung's study [3] shows the highest evidential value due to the lowest risk of bias.

4. Discussion

The pathomechanism of root resorption during orthodontic treatment is the effect of the damage of cementoblasts and precement, as well as an imbalance between the resorption effect of osteoclasts and the apposition effect of cementoblasts during the action of a stimulating factor. A symptom of root resorption is a change in shape and shortening of tooth roots to varying degrees [26–28]. In order to inhibit resorption, the stimulator must stop working. In orthodontic treatment, this means disabling any orthodontic forces to allow the osteoblasts to rebuild lost tissue. In the case of first and second degrees of resorption, the shape of the apex changes, while in the case of circular apical resorption (third degree), the length of the root is irreversibly shortened [26–28].

In addition, according to the latest knowledge, photomodulations such as low-level laser therapy (LLLT), light-emitting diodes (LED) and low intensity pulsed ultrasound (LIPUS) can have a positive effect on the average total root resorption [29].

Incisor resorption may be associated with incisor retraction. Important factors include the extent of retraction and the degree of torque control. The studies reviewed show that the extent of retraction is individualised and strictly dependent on the patient's anatomical structures, while the degree of torque control is important during retraction because of the ability to assess the degree of root displacement in the maxillary structure. The analysis of CT scans of different patients pointed to the existence of four main shapes of the incisive canal, listed according to their frequency [23]: funnel-shaped, cylindrical-shaped, hourglass-shaped and banana-shaped (Figure 3). This canal can be straight (<10 deg. to the plane of the palate), slanted (>10 deg. to the plane of the palate) and may also be characterised by additional curvature [1].

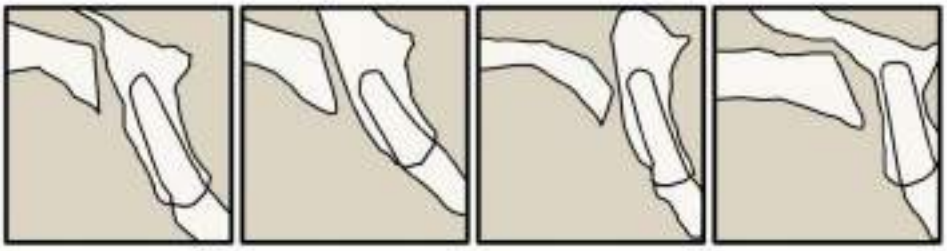

Figure 3. Variety of shapes and courses of the incisive canal [1].

According to the study by Arnaut, whose results overlapped with those of Milanovic and Thakur, the shape of the incisive canal itself has no relation to gender [23,30,31]. The average canal length obtained by Arnaut et al. and Bornstein et al. is slightly over 10 mm [23,32]. Meanwhile, the analysis of axial CBCT sections provided information that the average width of the incisive canal was 3.59 mm [23,31,33]. Importantly, according to the study by Cho et al., the incisive canal was wider than the inter-root distance in more than 60 percent of the patients [34]. The average anterior-posterior distance between the central incisors roots in the maxilla and the incisive canal is 5–6 mm [34,35]. The detailed results of the study by Arnaut et al. on the morphology and shape of the IC also showed that the diameter of the incisive canal depends on shape and was significantly increased in those with a banana shape, and decreased in those with a cylindrical shape [23]. This suggests that patients with the banana-shaped incisive canal are more prone to contact between the roots and canal during retraction than others. An increase in the distance between the roots and the incisive canal in the apical direction was also observed. Therefore, in the era of 3D imaging, it is worthwhile to individually plan the anatomically possible extent of retraction and case-appropriate torque control during retraction, and perhaps to use brackets with built-in greater angulation for maxillary incisors to increase the interapical distance and thus allow the roots to bypass the IC [23,34,36,37]. A reduction in the AP NF dimension in the case of the banana shape is a limiting factor for tooth retraction. At the same time, a cylindrical-shaped canal is accompanied by a higher risk of root invasion after retraction due to a significant reduction in the space required for retraction movement [23].

On the other hand, the analysis by Al-Rokhami et al. on the relationship of canal morphology with growth direction, skeletal class and gender showed that women with an increased vertical jaw relation are more likely to have contact between the roots and the incisive canal due to the width of the canal being greater than the inter-root distance, especially at the level of the incisive foramen H2, i.e., half the distance between the root apex and the lowest point of the incisive foramen on the buccal wall [35] (Figure 4). In patients with an incisive canal wider than the inter-root distance, it is worth considering the use of brackets with integrated greater angulation on the maxillary incisors. The retraction of incisors after previous maxillary expansion with palatal suture expansion or maxillary distraction osteogenesis may require special care and careful diagnosis due to the concomitant widening of the incisive canal—a subject worthy of attention and careful research. Furthermore, it was shown that the incisive canal is closer to the roots in high-angle patients than in medium- and low-angle patients. In addition, men are characterised by greater sagittal distances of incisor roots to the canal compared to women. The analysis of the above information suggests that high-angle women are at greater risk of contact with the incisive canal.

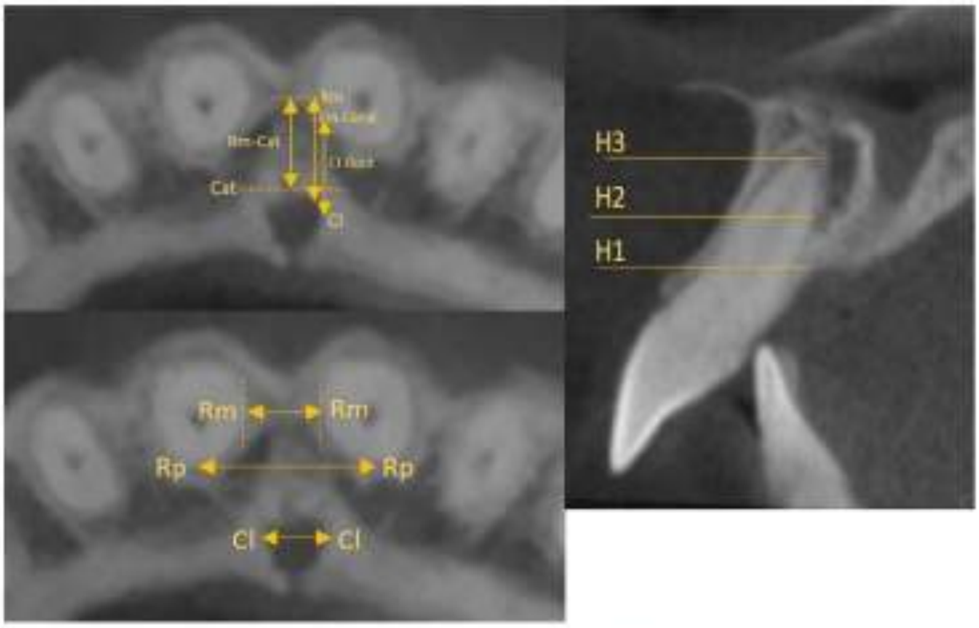

Figure 4. Topography and linear measurements [35].

According to the study by Arnaut, whose results overlapped with those of Milanovic and Thakur, the shape of the incisive canal itself has no relation to gender [23,30,31]. The average canal length obtained by Arnaut et al. and Bornstein et al. was slightly over 10 mm [23,32]. Meanwhile, the analysis of axial CBCT sections provided information that the average width of the incisive canal was 3.59 mm [23,31,33]. Importantly, according to the study by Cho et al., the incisive canal was wider than the inter-root distance in more than 60 percent of the patients [34]. The average anterior–posterior distance between the central incisors' roots in the maxilla and the incisive canal was 5–6 mm [34,35]. The detailed results of the study by Arnaut et al. on the morphology and shape of the IC also showed that the diameter of the incisive canal depended on shape and was significantly increased in those with a banana shape, and decreased in those with a cylindrical shape [23]. This suggested that patients with the banana-shaped incisive canal are more prone to contact between the roots and canal during retraction than others. An increase in the distance between the roots and the incisive canal in the apical direction was also observed. Therefore, in the era of 3D imaging, it is worthwhile to individually plan the anatomically possible extent of retraction and case-appropriate torque control during retraction, and perhaps to use brackets with built-in greater angulation for maxillary incisors to increase the interapical distance and thus allow the roots to bypass the IC [23,34,36,37]. A reduction in the AP NF dimension in the case of the banana shape is a limiting factor for tooth retraction. At the same time, a cylindrical-shaped canal is accompanied by a higher risk of root invasion after retraction due to a significant reduction in the space required for retraction movement [23].

Additional data on contact risk were presented in the study by Costa et al. Their results showed that low-angle patients have a thicker alveolar bone in the maxillary anterior area, which translates into greater distances between the roots and the incisive canal. They found no relationship between the facial profile and canal volume. However, they noted that men had a wider canal than women regardless of growth direction [38]. Canal height did not differ significantly between adults and adolescents, but was significantly lower for patients with contact after retraction, suggesting that the low position of the incisive canal may be a risk factor.

In the studies by Matsumura et al. and Linjawi et al., a significantly positive relationship was noted for the angles between the incisive canal and the palatal plane as well as between the long axis of the central incisors and the palatal plane—the more tilted the incisors, the more slanted the incisive canal [36,39]. Consequently, orthodontic treatment involving incisor tilting and retraction increased the risk of contact in these patients, mainly in the lower root half and cervical area. Thus, analysing the above, it can be concluded that excessive tilting may favour cervical resorption, whereas excessive torque may favour apical resorption. The use of 3D imaging and the visualisation of the incisive canal drew the attention of researchers to the importance of its morphology, shape, course and the possible relationship with incisor root resorption occurring after retraction. The amount of studies on the change in incisor root length due to contact with the IC is fairly limited, and all of them are retrospective. In this systematic review, all of them showed a positive relationship between the degree of resorption and the reduction in the distance from the roots to the IC. In addition, the study by Yu et al. [1] demonstrated the possibility of remodelling the canal in response to orthodontic tooth movement, which was accompanied by a lower degree of resorption. In 11.4 percent of the patients, a change in canal direction from slanted-straight to slanted-curved was observed after retraction. Further high-quality studies are needed that would perhaps make the remodelling ability of the IC dependent on the force applied, the tooth displacement times or other orthodontic factors, possibly reducing the number of root resorption complications. A statistically significant difference in the length of the roots not having and having contact with the incisive canal after orthodontic treatment with incisor retraction has been proven in controlled clinical prospective trials included in this systematic review with a moderate risk of bias.

5. Limitations

The main limitations of the review include articles written in English, which may affect the risk of bias of this publication. Furthermore, the amount of studies analysing the topic addressed was considerably limited. Controlled clinical retrospective trials and case reports were analysed due to the lack of randomised clinical trials and controlled clinical prospective trials. The inability to test the heterogeneity of the studies prevents the conduction of a meta-analysis.

6. Conclusions

The studies showed that contact between the upper incisor roots and the incisive canal significantly increased the risk of resorption of these roots. The diversity of the morphology of the incisive canal and its relationship to incisor roots suggests the need for more accurate diagnosis using 3D imaging, and the extent of possible retraction without a high risk of resorption and individualised control of incisor torque during retraction.

The incisive canal may have a remodelling ability in response to orthodontic displacement—more thorough research is needed to show this ability as dependent on factors such as age, gender or applied force.

Further high-quality studies—primarily RCTs with clearly defined methodology—are needed for better quality analyses and more reliable conclusions.

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Abbreviations

The following abbreviations are used in this manuscript:

PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PICO	Population, Intervention, Comparison, Outcome
RCT	Randomised Clinical Trial
CCT	Controlled Clinical Prospective Trial
ROBINS-I	Risk of Bias In Non-Randomised Studies of Interventions
CBCT	Cone Beam Computed Tomography
TISAD	Temporary Intraoral Skeletal Anchorage Device (orthodontic mini-implant)

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8.7. Publikacja 7

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Morphological Evaluation of the Incisive Canal in the Aspect of the Diagnosis and Planning of Orthodontic Treatment—CBCT Study

Anna Ewa Kuc [1,*], Jacek Kotula [1], Jakub Nawrocki [1], Ewa Szeląg [1], Beata Kawala [1], Joanna Lis [1] and Michał Sarul [2]

[1] Department of Dentofacial Orthopaedics and Orthodontics, Wroclaw Medical University, Krakowska 26, 50-425 Wroclaw, Poland; j_kotula@poczta.onet.pl (J.K.); ewa.szelag@umw.edu.pl (E.S.); beata.kawala@umw.edu.pl (B.K.); joanna.lis@umed.wroc.pl (J.L.)
[2] Department of Integrated Dentistry, Wroclaw Medical University, 50-425 Wroclaw, Poland; michal.sarul@umw.edu.pl
* Correspondence: annaewakuc@wp.pl

Abstract: Background: Understanding the anatomy of the incisive canal is crucial for effective diagnosis and treatment planning in clinical orthodontics. This is because, during orthodontic tooth movement, there is a risk of contact between the roots of the upper central incisors and the incisive canal. Objective: The aim of this study was to assess the anatomical variability of the incisive canal using cone beam computed tomography (CBCT), as well as to evaluate its correlation with age, sex, and the position of the maxillary central incisors. There are only a few studies on this topic. Materials and methods: We analysed CBCT data from 67 patients aged from 13 to 49 years. This study was conducted at the Wroclaw Medical University. Measurements were performed twice by two independent researchers, and intra-observer error and correlation were calculated. The mean difference between the first and second observations and between observers was also assessed. We examined the dimensions of the incisive canal and its relationship to the roots of the upper central incisors in relation to age and gender. Results: Our study results revealed a significant correlation between the width and length of the incisive canal. Males exhibited a significantly greater canal length at the lowest point of the incisive canal on the palatal wall. Additionally, males had wider canals compared to females. The analysis of canal width and distance between the most mesial point of the root and the line passing through the most anterior point of the incisive canal showed a negative correlation in all age groups of men. The analysis of incisal inclination and incisal canal inclination showed a very strong relationship, especially in the age group of 13 to 20 years. Several potential risk groups of contact between the roots of central incisors and the incisive canal have been identified based on their structure and the planned incisors' orthodontic movement. Conclusions and implications: Knowledge of the anatomy of the incisive canal and the use of 3D imaging in high-risk patients can prevent resorption of the incisor root by considering the individual anatomical conditions of the patient when planning orthodontic tooth movement. We recommend performing a CBCT scan before starting orthodontic treatment in the case of moderate and significant retraction of the incisors, or a significant change in their inclination due to the wide anatomical diversity of the incisive canal, especially in adult patients.

Keywords: anatomy; CBCT; root resorption; incisive canal; nasopalatine canal; retraction; radiology; orthodontic treatment; orthodontic diagnosis; orthodontic treatment planning

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1. Introduction

Orthodontic treatment of class II and III skeletal malocclusions, both through camouflage and orthognathic surgery, is associated with appropriate orthodontic preparation involving proclination (labial movement), lingual movement, retraction, or torque movements of the upper incisors. Since all these manipulations occur in the anterior segment of the maxilla, the anatomy of this area is of key importance in the diagnosis and planning of orthodontic movements that will not violate the bone envelope of this section and will not lead to the direct contact of the maxillary incisor roots with the palatal/vestibular cortical bone or the cortical bone of the incisive canal. Previous studies by other authors have shown that such contact may cause complications such as incisor root resorption, and dehiscence and/or fenestration [1–6]. A systematic review found that the risk of incisor root resorption is increased by root contact with the incisive canal [5]. Accurate diagnostics based on 3D imaging are needed to assess the diversity of the morphology of the incisive canal and its relationship with the incisor roots.

The incisive canal serves as a communication between the oral and nasal cavities. It ends in the oral cavity in the incisal fossa below the incisive papilla, immediately behind the upper central incisors [6]. It is surrounded on each side by thick cortical bone and contains nerves and vessels supplying the upper incisors and the anterior part of the palate. The assessment and knowledge of the anatomical features of the incisive canal, its structure, size, and changes in inclination depending on age, sex, as well as parameters determining the position of the maxillary incisors, can help effectively prevent severe complications of orthodontic treatment, such as root resorption. These need investigation due to the insufficient assessment of this region on routinely performed panoramic radiographs and cephalometric images [7].

The growth and development of soft and hard tissues are closely function-related. Since the skeletal unit is responsible for protecting and supporting the functional matrix, the size, shape, and position of anatomical structures change in order to meet the functional needs [8]. Therefore, it is very likely that the anatomy of the incisive canal may depend on age, sex, position of the upper incisors, direction of facial growth, and muscle activity. It may also be more or less susceptible to reconstruction and remodelling resulting from orthodontic manipulations, depending on parameters such as age, sex, or applied orthodontic forces [1].

As a result of advances in 3D imaging in recent years, publications showing the morphological diversity of the incisive canal have appeared. However, their results are ambiguous. Some studies [8–19] indicated a significant impact of sex, age, and growth direction on the anatomical and morphometric features of the canal, supporting the need to consider the risk of complications when planning orthodontic and surgical interventions involving the anterior maxilla. However, others [6,7,20] have not shown such a relationship. Therefore, prior to orthodontic range of motion planning, it is important to identify high-risk patient groups that require thorough diagnostics, including CBCT of this segment, to minimise this risk. For years, there has been a debate as to whether CBCT should be performed before orthodontic treatment. Risk analysis in individual age and sex groups may answer the question of whether such an extended diagnosis is indicated.

Cephalometric images are routinely used in orthodontic treatment planning, especially to assess the anterior-posterior relationship where the ANB angle is considered the gold standard in assessing the sagittal-mandibular relationship [21]. However, neither this nor a panoramic radiograph is sufficient to illustrate the area of the incisive canal in relation to the upper incisors.

Objective

The aim of this study was to define risk groups according to the anatomical variability of the incisive canal using cone beam computed tomography (CBCT), as well as to evaluate the correlation of the canal shape (width, length, and inclination) with age, sex, and position of the upper central incisors. There are only a few studies on this topic.

2. Materials and Methods

2.1. Participants

This study used CBCT records found in the resources of the Department of Maxillofacial Orthopaedics and Orthodontics of the Wroclaw Medical University. CBCT images of 67 patients (35 women and 32 men) aged 13 to 49 years were analysed. CBCT scans taken between 2017 and 2021 prior to orthodontic treatment were used as part of the orthodontic diagnostic process.

The criteria for inclusion of the patient's CBCT records in the study group were as follows:

(1) Complete development of the upper incisor roots.
(2) Clearly visible maxilla.
(3) Patients with permanent dentition.
(4) Without a history of orthodontic treatment.
(5) Generally healthy patients with no history of bone diseases.

Exclusion criteria:

(1) Missing maxillary incisor(s).
(2) Maxillary incisor pathology.
(3) Developmental anomalies of the incisive canal (additional canals in the area of the incisive canal, as well as clear asymmetries).
(4) Poor quality of CBCT, preventing accurate measurements.
(5) The presence of imaging artifacts hindering measurements in the anterior maxillary region.
(6) Incomplete root development.
(7) Root resorption due to trauma or inflammation.
(8) History of previous orthodontic treatment.

The participants were classified into groups according to sex and age. Four age groups (16–18 participants) have been created:

A. 13–20 years.
B. 21–29 years.
C. 30–39 years.
D. 40–49 years.

Ethical approval from the Bioethical Committee of the Wroclaw Medical University was granted for our study (nr KB-231/2021, accessed on 19 March 2021), providing that all the data were anonymised (as was the cases in our study). In accordance with the decision of the bioethics committee, patients were comprehensively informed about the assumptions, risks, consequences for the body, and benefits of the study. Patients received a full written justification and information that they could withdraw from the study at any time without any consequences for their participation in the comprehensive orthodontic treatment process. Patients under 18 years of age as well as their parents signed with informed consent to participate in the study.

Patients over the age of 13 were included in the study because the treatment of patients of this age requires the use of fixed appliances, which are used to carry out precise, large-scale tooth movements. Significant tooth movements during treatment with fixed appliances significantly affect the possibility of roots of the central incisors contacting with the incisive canal. In treatment with removable appliances at an earlier age, such significant shifts are not made, which is associated with a lower risk of contact of the roots of the central incisors with the incisive canal. Therefore, the potential benefits of such diagnostics outweigh the health costs associated with exposing younger children, even before their growth spurt, to the significant risks from absorbed radiation associated with CBCT projection.

2.2. Data Acquisition and Measurements

CBCT was performed with a CS 9600 Carestream Dental. The exposure parameters were as follows: 120.00 KV, 6.3 mA, an exposure time of 20.00 s, and a dose of 814.18 mGy/cm^2. The Frankfurt plane was parallel to the floor. CS 3D Imaging (Carestream Dental LLC) was used for measurements. The measurements were performed twice independently by two investigators (experienced orthodontists with many years of experience), and the mean result was used in the statistical analysis. Intra- and inter-observer reliability tests were performed for CBCT measurements, $p < 0.005$.

The following measurements were taken:

A. Horizontal plane separately for each level—L1, L2, and L3:
   1. Incisive canal width—|Cl-Cl|.
   2. Antero-posterior IC—|Ca-Cp|.
   3. Distance between the most mesial point of the root and the tangent passing through the most anterior point of the incisive canal—|Rm-Cat|.
   4. Distance from Cl to the posterior edge of the incisor root—|Cl-Rpt|.
   5. Distance between roots |Rm-Rm|.

B. Sagittal plane:
   1. Angle formed by the long axis of the incisor and the palatine plane—CP angle.
   2. Angle formed by the long axis of the incisive canal and the palatine plane—IP angle.

C. Coronal plane:
   1. Angle formed by the long axes of the central incisors (values above zero for convergent roots, negative values for divergent roots).

L1, L2, and L3 were determined in sagittal planes as follows: L1—the lowest point of the incisive canal on the palatal wall, L2—half the distance between L1 and L3, and L3—the height of the top of the maxillary central incisor (Figure 1).

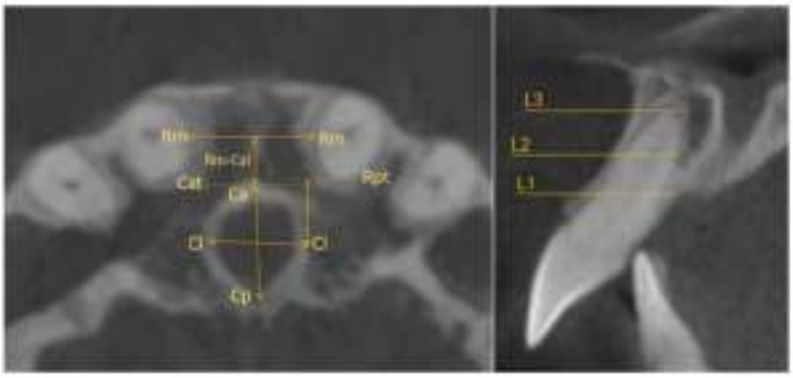

Figure 1. Measurement scheme.

Measurement landmarks:
Rm—the most mesial point of the root U1.
Rp—the most posterior point of the root U1.
Cl—the most lateral point of the incisive canal.
Ca—the most anterior point of the incisive canal.
Cat—tangent to Ca.
Rpt—tangent to Rp.

The long axis of the incisor was determined by connecting the incisal edge with the root apex (Figure 2).

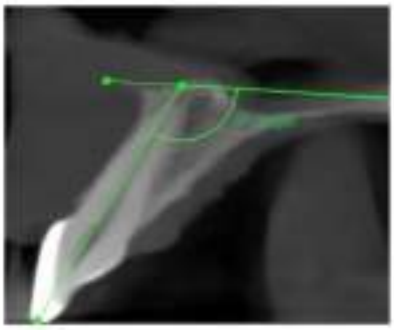

Figure 2. An angle formed by the long axis of the incisor and the palatal plane.

The long axis of the canal was determined by connecting a point midway between the labial and palatal walls of the incisive foramen and a point midway across the width of the canal in the predetermined palatal plane (Figure 3).

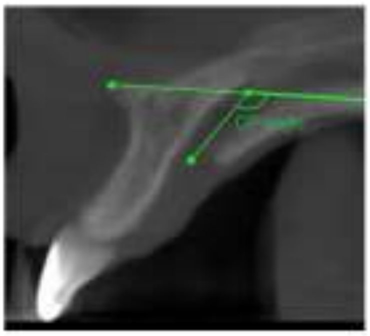

Figure 3. An angle formed by the long axis of the incisive canal and the palatal plane.

2.3. Statistical Analysis

The analysis of the research results was carried out using the statistical package Statistica 13.3 by Tibco. After determining the basic statistical measures, the hypothesis of the normality of the empirical distribution was verified using the Kolmogorov-Smirnov (K-S) and Shapiro-Wilk (S-W) tests. The normality of the distribution of variables was also assessed graphically using histograms and standard probability plots of the variables.

In the case when at the significance level of $p = 0.05$, the null hypothesis H_0 was adopted. If the distribution of the analysed variable is normal, parametric tests, the t-test or the classic ANOVA analysis of variance were performed. In addition, for the ANOVA analysis, the assumption about the homogeneity of variance in the groups was verified by performing a Levene's test. After the verification of the assumptions of the ANOVA test and rejection of the null hypothesis of no differences in the compared populations, post-hoc tests were performed.

For selected groups of variables, a correlation analysis based on the Pearson linear correlation coefficient was performed. The assessment of the interdependence of variables was based on the Guilford classification [22]:

$|r| = 0$—no correlation.

$0.0 < |r| \leq 0.1$—almost no correlation.

$0.1 < |r| \leq 0.3$—weak correlation.

$0.3 < |r| \leq 0.5$—moderate correlation.

$0.5 < |r| \leq 0.7$—high correlation.
$0.7 < |r| \leq 0.9$—very high correlation.
$0.9 < |r| < 1.0$—almost complete correlation.
$|r| = 1$—complete correlation.

In the next part, a test of the significance of the correlation coefficient was performed. This test was carried out in order to check whether the determined correlation in the tested sample also occurs in the population from which the sample was taken.

The power of the tests is not less than 0.6 with a significance level (type I error) of 0.05 performance.

For each of the tests performed, the differences were considered statistically significant if $p < 0.05$.

3. Results

3.1. *Width vs. Length of Incisal Canal*

3.1.1. Level 1 (L1)

The analysis of the correlation between the width and length of the canal showed varied results. For the whole group of patients, this correlation was statistically significant ($p < 0.05$), but moderate ($r = 0.375$), and indicated an increase in the length of the canal with an increase in its width. This correlation was found to be high ($r = 0.557$, $p < 0.05$) in the male group, but weak and statistically insignificant in the female group ($r = 0.150$, $p < 0.05$). Interestingly, the results varied between age groups. A very high and statistically significant correlation ($r = 0.845$, $p < 0.05$; $r = 0.761$, $p < 0.05$) was found in the 13 to 20-year-old women and men group, showing a linear increase in the dimensions of the incisive canal and a relationship between length and width. This high to very high correlation was maintained in the group of men and women aged 21 to 29 years ($r = 0.729$, $p < 0.05$) and in the total group of men, regardless of age. A different situation was observed among women over 30 years of age, where a negative, moderate, and statistically insignificant correlation was found, indicating that the length of the canal decreased with increasing width (Table 1).

Table 1. Width (Cl-Cl) vs. length (Ant—post dimension of the canal) of incisal canal—L1.

Gender/Age	Mean Width (SD)	Mean Length (SD)	r(X,Y)	r^2	t	p
F 13–20	4 (±0.81)	4.49 (±0.97)	0.845	0.71	4.19	0
M 13–20	4.03 (±0.82)	4.53 (±1.57)	0.762	0.58	2.63	0.05
F 21–29	4.61 (±0.89)	4.16 (±0.62)	0.729	0.53	2.82	0.03
M 21–29	4.5 (±1.33)	4.79 (±0.52)	0.536	0.29	1.56	0.17
F 30–39	4.68 (±1.36)	4.01 (±0.8)	−0.318	0.1	−0.82	0.44
M 30–39	4.4 (±1.06)	4.73 (±0.82)	0.668	0.45	2.2	0.07
F 40–49	4.78 (±0.52)	4.27 (±0.62)	−0.417	0.17	−1.21	0.26
M 40–49	5.04 (±0.96)	4.79 (±1.14)	0.618	0.38	2.08	0.08

3.1.2. Level 2 (L2)

For the L2 level, a positive and high correlation was found both in all patients and by sex ($r = 0.687$, $p < 0.05$; $r = 0.752$, $p < 0.05$; $r = 0.621$, $p < 0.05$). This high correlation was maintained in all age groups, both female and male, reaching an almost full level in the group of men aged 21 to 29 years ($r = 0.945$, $p < 0.05$) (Table 2).

Table 2. Width (CI-CI) vs. length (Ant—post dimension of the canal) of incisal canal—L2.

Gender/Age	Mean Width (SD)	Mean Length (SD)	r(X,Y)	r^2	t	p
F 13–20	3.38 (±0.97)	3.46 (±0.56)	0.753	0.57	3.03	0.02
M13–20	3.66 (±0.98)	3.54 (±1.66)	0.629	0.4	1.81	0.13
F 21–29	4.29 (±0.87)	4.02 (±1.02)	0.815	0.66	3.72	0.01
M 21–29	3.86 (±1.43)	4.05 (±1.33)	0.945	0.89	7.08	0
F 30–39	4.19 (±1.33)	3.88 (±0.97)	0.361	0.13	0.95	0.38
M 30–39	4.14 (±1.13)	3.73 (±1.15)	0.876	0.77	4.45	0
F 40–49	4.66 (±0.64)	4.16 (±0.52)	0.479	0.23	1.44	0.2
M 40–49	4.22 (±1.12)	4.39 (±1.13)	0.623	0.39	2.11	0.07

3.1.3. Level 3 (L3)

For L3, there was also a positive high and very high correlation in all patients and all age groups, both in men ($r = 0.728$, $p < 0.05$) and women ($r = 0.655$, $p < 0.05$), with an almost complete correlation in women aged 21 to 29 years ($r = 0.935$ $p < 0.05$) and in men aged 30 to 39 years ($r = 0.920$ $p < 0.05$), while the strength of this relationship was lower and statistically insignificant in men aged 21 to 29 years and women aged 40 to 49 years compared to other groups (Table 3).

Table 3. Width (CI-CI) vs. length (Ant-post dimension of the canal) of incisal canal—L3.

Gender/Age	Mean Width (SD)	Mean Length (SD)	R(X,Y)	r^2	t	p
F 13–20	3.93 (±1.13)	3.59 (±0.95)	0.72	0.52	2.75	0.03
M13–20	3.49 (±1.2)	3.53 (±1.58)	0.729	0.53	2.38	0.06
F 21–29	3.68 (±0.8)	3.77 (±1.25)	0.936	0.88	7.03	0
M 21–29	3.28 (±0.9)	2.94 (±0.8)	0.128	0.02	0.32	0.76
F 30–39	4.06 (±1.19)	3.43 (±1.09)	0.678	0.46	2.26	0.06
M 30–39	4 (±1.59)	3.24 (±1.63)	0.921	0.85	5.78	0
F 40–49	4.46 (±1.02)	4.2 (±1.17)	0.423	0.18	1.23	0.26
M 40–49	4.49 (±0.97)	3.83 (±0.93)	0.71	0.5	2.67	0.03

3.1.4. Width and Length across Groups

The width of the canal at the L1 level was similar for both men and women, while its length differed considerably and statistically significantly ($p < 0.05$) and was greater in men than in women. At the L2 level, both width and length were similar in women and men. At the L3 level, the width was still similar, while the length differed significantly and was smaller in men vs. women. Considering age groups, a high variation was observed in the 21 to 29-year age group, where the L1 canal length was definitely higher in men than in women, with similar findings in the 30 to 39-year and the 40 to 49-year age groups. The values were similar for other levels and other groups.

3.2. Width vs. Inclination of the Upper Central Incisors (Convergent/Divergent)

3.2.1. L1 level

Angulation of the upper central incisors did not correlate with canal width when analysing the total group or by sex. The absence of a correlation was statistically significant. However, a high correlation was found at the L1 level in both women and men aged 13 to 20 years. This correlation was negative in the group of women ($r = -0.617$), which means that the interapical distance increases with increasing canal width, while in the case of men ($r = 0.640$), this correlation was positive, i.e., the wider the canal, the more convergent the roots. A high positive correlation was present in the group of men up to 30 years of age. Patients aged 30 to 39 years showed strong negative correlations. A strong negative correlation was found in women up to 40 years of age. Between the ages of 21 and 40 years, the correlation was also negative but less strong. Correlations in the age groups did not show statistical significance (Table 4).

Table 4. Width (CI-CI) vs. inclination of upper central incisors (convergent/divergent)—L1.

Gender/Age	Mean Width (SD)	Mean Inclination of the Central Incisors (SD)	r(X,Y)	r^2	t	p
F 13–20	4 (±0.81)	0.11 (±6.13)	−0.617	0.38	−2.08	0.08
M13–20	4.03 (±0.82)	−1.29 (±7.95)	0.64	0.41	1.86	0.12
F 21–29	4.61 (±0.89)	−1.72 (±4.8)	−0.492	0.24	−1.49	0.18
M 21–29	4.5 (±1.33)	−2.13 (±5.79)	0.623	0.39	1.95	0.1
F 30–39	4.68 (±1.36)	−4.13 (±6.03)	−0.225	0.05	−0.57	0.59
M 30–39	4.4 (±1.06)	0.63 (±2.77)	−0.536	0.29	−1.55	0.17
F 40–49	4.78 (±0.52)	−1.11 (±8.51)	−0.53	0.28	−1.65	0.14
M 40–49	5.04 (±0.96)	−1.61 (±4.41)	0.262	0.07	0.72	0.5

3.2.2. L2 Level

At the L2 level, correlations of varying strength were observed, and the trend in both men and women was similar to that at the L1 level. The exception was the group of men aged 30 to 39 years where, unlike other groups of men, the correlation was high and negative (r = −0.546), but statistically insignificant.

3.2.3. L3 Level

No correlations were found at the L3 level.

3.3. Inclination of the Incisors (Angle Formed by the Long Axis and the Palatal Plane) vs. Inclination of the Incisal Canal

A positive and very strong correlation was found between the inclination of the incisors and the inclination of the canal in the group of women aged 13 to 20 (r = 0.828, $p < 0.05$) and 40 to 49 years (r = 0.603). In the case of men, a moderate and negative correlation was observed between 13 and 20, and 30 and 39 years of age (r= −0.429; r= −0.495; $p > 0.05$), respectively. A strong, positive, and statistically significant correlation was found for those aged 20 to 29 years (r = 0.868, $p < 0.05$). In the general breakdown by sex, only women showed a statistically significant, yet moderate, correlation between these parameters. Graphs presenting statistical values for incisor and canal inclination in women and men confirm the above relationships (Table 5).

Table 5. Incination of the incisors (angle formed by the long axis and the palatal plane) vs. inclination of the incisive canal.

Gender/Age	Mean Angle Formed by the Long Axis of the Incisor and the Palatal Plane (SD)	Mean Angle Formed by the Long Axis of the Incisal Canal and the Palatal Plane (SD)	r(X,Y)	r^2	t	p
F 13–20	113.33 (±7.25)	107.44 (±10.91)	0.828	0.69	3.91	0.01
M13–20	115.71 (±11.86)	103.14 (±7.29)	−0.429	0.18	−1.06	0.33
F 21–29	109.11 (±11.03)	105.22 (±9.34)	0.238	0.06	0.65	0.54
M 21–29	113.38 (±6.23)	109.13 (±8.2)	0.868	0.75	4.28	0.01

Table 5. *Cont.*

Gender/Age	Mean Angle Formed by the Long Axis of the Incisor and the Palatal Plane (SD)	Mean Angle Formed by the Long Axis of the Incisal Canal and the Palatal Plane (SD)	r(X,Y)	r^2	t	p
F 30–39	99.63 (±7.67)	102.63 (±6.23)	0.385	0.15	1.02	0.35
M 30–39	113.88 (±5.79)	107.25 (±3.77)	−0.496	0.25	−1.4	0.21
F 40–49	104.78 (±14.4)	105.44 (±7.73)	0.603	0.36	2	0.09
M 40–49	109.33 (±9.59)	112.67 (±8.93)	0.169	0.03	0.45	0.66

3.4. *Width vs. Ror-Cat*

The relationship between canal width and the distance between the most mesial point of the root and the tangent passing through the most anterior point of the incisive canal was observed only in the men's group and was negative in all age groups. This indicates that the wider the canal, the closer the roots are to the cortical bone of the incisive canal. On the other hand, a very strong and strong correlation was observed in the group of men aged 13 to 20 years ($r = -0.745$) and 40 to 49 years ($r = -0.578$) at L1. At L2, this strong negative correlation occurred only in the group of men aged 13 to 20 years ($r = -0.565$). However, at the L3 level, a strong negative correlation was found in all age groups, except for the group aged 30 to 39 years. In the case of women, a strong and positive correlation at the level of L1 and L3 was found only in the age group of 40 to 49 years ($r = 0.677$, $p < 0.05$; $r = 0.662$). This means that the narrower the canal, the closer it is to the roots. In other cases, the correlation was either almost absent or weak. Taking into account the general division between women and men, the correlation was absent and statistically insignificant, while in men a moderate but statistically significant correlation was observed. The results of the group were statistically significant only at the L1 level in the group of women aged 40 to 49 years.

3.5. *Width, Length vs. Age, and Sex*

No significant relationship was observed between the group of women and men in terms of canal width. Canal length was definitely shorter in women than in men at L1, the same at L2, and definitely longer at L3. It showed the greatest discrepancies at all levels in the youngest group of 13 to 20 years old, both in women and men. Characteristically, the length of the canal at the L1 level decreased in women up to the age of 39 years and increased again after the age of 40 years. In men, the length of the canal at this level was similar between all age groups. In women, we observed an increase in the anteroposterior dimension of the L3 canal with age, while in men it remained at a similar or slightly increased level. None of the results were statistically significant ($p > 0.05$). The mean width of the canal at L1-L3 was 4.52 mm, 4.09 mm, and 3.94 mm, respectively, while the anteroposterior measurement was 4.47 mm, 3.92 mm, and 3.58 mm, respectively.

3.6. *Incisor Inclination vs. Age and Sex*

It was observed in women that the inclination of the incisors relative to the maxillary base decreased with age up to 40 years of age, after which point it began to increase, in contrast to men, where the inclination of the incisor increased with age, but without a statistically significant level.

3.7. *Ror-Cat vs. Angulation of the Upper Central Incisors (Convergent/Divergent)*

CBCT showed a negative correlation in the group of young men aged 13 to 20 years ($r = -0.930$, $p < 0.05$), at all levels between the angulation of the roots of the upper central incisors and the distance between the most mesial point of the root and the tangent passing through most anterior canal point. It can be assumed that the more convergent the roots, the smaller the distance to the canal. In the case of women, a similar correlation occurred only at the age of 40 to 49 years ($r = -0.554$) and was statistically insignificant.

4. Discussion

The purpose of this study was to assess parameters such as width, anteroposterior length (AP), and inclination of the incisive canal depending on age, sex, and inclination of the upper incisors, and to identify a correlation between these parameters. This will allow the identification of groups of patients with an increased risk of complications in the form of resorption of incisor roots treated orthodontically. Knowing the risk of complications related to the anatomical structure of the incisive canal, it may turn out that an orthodontic compromise will be necessary in a certain population of patients to protect the roots and the periodontal apparatus rather than strive to achieve cephalometric standards. Previous studies have focused mainly on the analysis of the shape of the canal, its length from the nasal cavity to the oral cavity, the average diameter of the canal, as well as the relationship of these parameters with age, sex, type of malocclusion, or direction of facial growth [12–15,20,23,24].

Our research assessed the width of the canal in relation to age and sex. We described a relationship between the canal width and the angulation of the central incisors, as well as a correlation between the incisor inclination and the canal inclination.

There was a clear relationship between the width of the canal and its AP length. In most age groups, the increased canal length was accompanied by an increased width at all levels (L1, L2, and L3). This means that people with a wide canal who require posterior root movement may be at an increased risk for two reasons. This is primarily due to the increased length of the AP canal. This may result in a smaller initial root-to-canal distance. Additionally, the width of the canal may exceed the inter-root distance between the central incisors. Only women over 30 years of age showed a negative correlation of these two parameters, i.e., they are characterised by a larger canal width than length. The inter-root distance in relation to the canal width may be of greater diagnostic importance in these patients than the AP root distance from the canal.

Due to the significantly greater canal length at L1, men had a higher risk of cervical root-canal contact than women. In women, the length of the AP canal was definitely greater at L3 than in men. In the group of women, more attention should be paid when planning treatment involving axial retraction, torquing, or inclination of the incisor root due to the greater risk of apical contact.

Studies in women have shown that the divergence of the incisor root increases with increasing canal width, which seems logical. For men aged 13 to 30 years, this correlation was negative, i.e., the wider the canal, the more parallel or convergent the roots. The analysis of the above data, especially at the L1 level, should lead to a more extensive diagnosis in men with parallel or convergent incisors on a panoramic radiograph. In this situation, there is a high likelihood that contact with the incisive canal will occur during incisor retraction or excessive torquing. This is due to the interapical distance being smaller than the width of the canal. It is this structure, not the cortical bone of the palate of the maxillary alveolar process, that may stand in the way and determine the degree of possible retraction. Women may be less at risk of resorption in this regard. This is all the more important as studies by Cho et al. showed that in over 60% of patients, the width of the canal is greater than the interroot distance [14].

Analysis of the incisor inclination and the incisive canal inclination showed a very strong relationship, especially in the age group of 13 to 20 years. In women, the canal inclination increased with the increasing posterior movement of the incisors, while in men the opposite occurred. This parameter indicates a potential increased risk of resorption in this group of women in the case of excessive posterior movement of the incisors. The risk of pericervical contact is increased here. Men are probably at less risk in this respect, but more research is needed on this topic. Similar results were seen in women aged 40 to 49 years and men aged 30 to 39 years. When planning the treatment of upper incisor protrusion, the structure of the palatal canal should be taken into account, especially in connection with the posterior rotation of the mandible. Studies have shown that individuals with posterior mandibular rotation have a narrower maxillary alveolar ridge [8].

Analysis of canal width and distance between the most mesial point of the root and the tangent passing through the most anterior point of the incisive canal showed a negative correlation in all age groups of men. The wider the canal, the shorter the distance between the roots and the canal. This may be related to the convergence of the incisors in the case of larger canal widths. The strongest correlation at the L1 level again confirms the increased risk of contact and possible resorption in the pericervical region in men. At L2, boys aged 13 to 20 years were most at risk. In women, the correlation at the level of L1 and L3 occurred in the age group of 40 to 49 years. The roots here were located closer to the canal, which had a reduced width. In women in this age group, there was an increased risk of excessive movement of the incisors within the tongue, e.g., in the case of decompensation of class III malocclusion. Different results were obtained by Costa et al. [8]. They found no gender-dependent relationship between the interroot distance of the upper central incisors and the anterior border of the incisal canal or the sagittal or vertical skeletal patterns.

Regarding the width of the canal in the aspect of gender, this research confirmed the results obtained by Costa [8]. Men had greater canal widths compared to women. Similar results were previously obtained [7,25,26]. Our research has confirmed the sexual dimorphism of the incisive canal. At the same time, it was noted that the incisive canal had a cross-sectional shape similar to a circle at the L1 level and an ellipse at the L3 level with a larger transverse dimension. These findings suggest that incisor retraction after maxillary expansion should be performed with care.

The increasing AP dimensions of the canal in women over 40 years of age at the L3 level suggests a greater risk in the case of axial retraction of the incisors, especially after maxillary osteodistraction, during which the width of the canal increases. On the other hand, increasing the width of the incisive canal in relation to the length of the anteroposterior with age in women up to 40 years of age also increases the potential risk of incisor resorption after maxillary expansion. This is due to the high risk of greater canal width than the interroot distance.

Various complications can occur during orthodontic treatment. Root resorption is mild in most cases and does not adversely affect the prognosis of the affected teeth. Unfortunately, some patients experience extensive root reduction, which may even lead to tooth loss. The etiology of resorption is not fully understood. In this place, contact of the roots with the vestibular or palatal cortical bone of the alveolar process is increasingly indicated. Similarly, the probability of resorption as a result of contact with the cortical bone surrounding the incisal canal can be assumed [1–5].

According to Kaley, the risk of severe resorption is highest in the case of the upper incisors and amounts to 3%, while the same risk increases 20 times when the roots are moved into contact with the palatal cortical plate of the alveolar process [27]. Similarly, contact with the cortical plate of the incisive canal may also increase the risk of resorption, which is discussed in detail in a systematic review on this topic [5].

Incisor retraction, excessive labial or lingual movement, and intrusion or extrusion are high-risk factors for resorption. Class II or III skeletal malocclusions, open and deep bites, which are managed after the end of growth, usually require either treatment with orthodontic camouflage or decompensation of the defect before orthognathic surgery. In both cases, an extensive range of orthodontic movement may be necessary, depending on the severity of the defect. Skeletal anchorage has contributed to the possibilities and scope of this movement, which does not change the fact that movement should still take place within the bone envelope. Knowledge of the anatomy of the incisive canal, which may interfere with retraction, torque, intrusion, and lingual movement of the upper incisors, e.g., during decompensation of class III malocclusion, is essential for the proper planning of orthodontic treatment. It reduces the risk of root resorption.

The anatomy of the incisal canal combined with the knowledge of the different widths of the maxillary alveolar bone may be crucial in preventing root resorption. Handelman [28] showed that patients with mandibular posterior rotation are characterised by a narrower maxillary alveolar process than those with anterior rotation. On the other hand, Sadek, Poraj, and Gracco [29–31] described a greater thickness of the alveolar process in the anterior part of the maxilla in brachycephalic patients. Furthermore, changes in the width of the maxillary alveolar ridge before and after retraction may be correlated with the magnitude of this movement. This suggests that greater diagnostic and therapeutic attention should be paid to patients with an initially narrow alveolar ridge [32]. Zhang [33] reported that the tipping of the incisor causes more bone resorption than axial movement. It is puzzling, however, that in some patients there is a strong root resorption as a result of contact of the root with the cortical bone, while in others, despite the bone separation, the entire roots are preserved. The applied orthodontic force may play a role, but further research is needed to confirm this hypothesis.

The structure of the incisive canal and the anterior part of the maxillary alveolar process are important for root torque. Ten, Hoeve, and Mulie [34] demonstrated root resorption that extended from the apex and along the palatal surface of the root. It developed as a result of excessive root torque. It could have been related to contact with both the cortical bone of the palatal and canal.

The last published study on the anatomy of the incisive canal determined the distance of the roots of the upper incisors from the canal depending on the growth pattern. There were gender differences, especially in the hypodivergent group. The authors also noted that this information may be useful in clinical practice [35].

Figures 4–11 show CBCT and X-ray images of a patient with resorption of the left upper central incisor root due to contact of the mesial and posterior part of the root with the cortical bone of the incisive canal after retraction and lingual movement of the upper incisors. Probably, earlier knowledge of such a risk could allow for the use of greater angulation of the incisors and bypassing of the cortical bone of the canal and, thus, prevent resorption. After analysing the images, it can be assumed that the height at which the root contacts the canal may determine the extent of resorption. The lower the height, the greater the root shortening. Further research is needed to confirm this hypothesis.

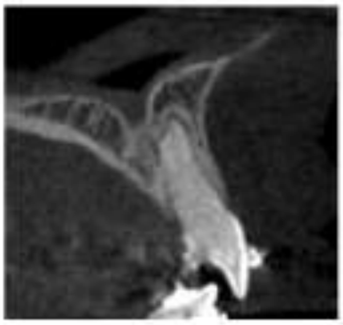

Figure 4. Root resorption of upper incisor after contact with incisal canal CBCT—sagittal plane.

Figure 5. Root resorption of upper incisor after contact with incisal canal CBCT—coronal plane.

Figure 6. Contact of upper incisor's root with incisal canal CBCT.

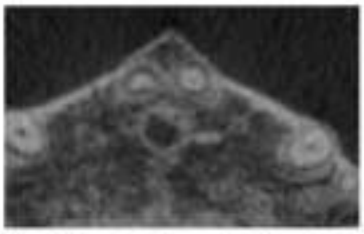

Figure 7. Contact of upper incisor's root with incisal canal CBCT.

Figure 8. Rtg before treatment.

Figure 9. Rtg during treatment.

Figure 10. Cephalometric before treatment.

Figure 11. Cephalometric during treatment.

When qualifying patients for one of the groups with a potential increased risk (Table 6) of root contact with the incisive canal and the palatal cortical bone, orthodontic diagnosis should be individualised. These patients need baseline CBCT, brackets with greater angulation for the upper central incisors, or treatment planning based on a setup with 3D imaging. It may turn out that during decompensation of class II and III malocclusions and open bite as preparation for orthognathic surgery, achieving the correct textbook parameters of the incisors would require violating the bone envelope and the associated resorption of the incisors. At this point, it seems most reasonable to accept an orthodontic compromise rather than strive at all costs for the goal, i.e., textbook cephalometric standards, following the principle of primum non-nocere. The validity of initial treatment consisting of maxillary widening and decompensation of the upper incisors during the growth period, even with extensive class III malocclusions or open bites qualifying for orthognathic treatment in adulthood, should also be considered so as to reduce the scope of surgery in the future and avoid movements of the upper incisors at risk of resorption. Previous studies have confirmed the possibility of alveolar bone remodelling in response to orthodontic movement in growing patients [36]. Unfortunately, the vestibular and palatine cortical bone as well as the cortical bone surrounding the canal may constitute "orthodontic walls" that should not be crossed in adults, as such movements can result in both root resorption and bone dehiscence [37]. Meanwhile, contact of the root with the cortical bone during malocclusion decompensation in conjunction with orthognathic procedures is a much stronger risk factor for incisor resorption, which may be additionally increased by long and narrow roots [38].

Table 6. Risk groups for sex, age, and orthodontic movements in relation to the anatomy of the incisive canal.

Risk Factor	Potential Risk Group
Incisive canal width	Males
AP canal length	Males—cervical (excessive lingual movement of the incisors) Females—apical (axial movement, torquing, and proclination) Females over 40 years—lingual movement, torquing and retraction, especially after osteodistraction
Root angulation of the upper central incisors (convergent/divergent)	Males aged 13–30 years (axial movement, excessive torque, and proclination)
Canal inclination vs. incisor inclination	Age 13–20 years Females—pericervical (lingual movement, excessive retraction) Males—apical (proclination, torque and axial movement)
Canal width vs. root distance from the canal	Males—pericervical (lingual movement, excessive retraction) Males 13–20—L2 (axial movement) Females over 40 years—pericervical and apical (all movements)

Taking into account the safety of orthodontic treatment, we should not forget about the levels of force released by orthodontic wires. They can vary significantly, with the same diameter, depending on the brand of wire, and also change due to the influence of the oral environment on the properties of the wire material itself [39–41].

One of the limitations of this study is the number of patients, its cross-sectional nature, and the associated limitations.

5. Conclusions

This research we carried out showed a different width of the incisal canal depending on the gender. The anteroposterior length of the canal largely depended on its width. The inclination of the canal depended on the inclination of the incisors in different age groups. The width of the canal depended on the sex-related converging or diverging position of the incisors. Knowledge of the anatomy of the incisive canal and the use of 3D imaging in high-risk patients can prevent resorption of the incisor root by considering the individual anatomical conditions of the patient when planning orthodontic tooth movement. It is reasonable to consider performing CBCT before the start of orthodontic treatment in the case of moderate and significant retraction of the incisors or a significant change in their inclination due to the high anatomical diversity of the incisive canal area, especially in adult patients.

More high-quality studies are needed, primarily RCTs with a clearly defined methodology, for better-quality analyses and more reliable conclusions.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available because the data was provided in a raw form to the statistician for analysis, potentially remaining incomprehensible to others without detailed explanations.

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9. Podsumowanie wyników

Publikacja 1

W wyniku przeszukania w bazach danych dotyczących nowych pomiarów cefalometrycznych w płaszczyźnie strzałkowej odnaleziono łącznie 1451 artykułów. Ostatecznie jedynie 12 artykułów spełniło kryteria włączenia określone w celach. W wyniku przeszukania bazy danych dotyczących nowych pomiarów w płaszczyźnie wertykalnej odnaleziono łącznie 1451 rekordów artykułów. Ostatecznie tylko 4 artykuły spełniły kryteria włączenia określone w celach.

Dowody sugerują, że istnieje wiele nowych punktów odniesienia i wskaźników cefalometrycznych takich jak kąty Tau, Yen, SAR, W, DW, Pi i analiza linijna Pi oceniające relacje sagitalne podstaw szczeki i żuchwy wzbogacające złoty standard analizy w postaci kąta ANB, które można z powodzeniem zastosować do określenia rozbieżności strzałkowej we wzajemnym położeniu podstaw szczęki. Jednakże, chociaż przegląd systematyczny charakteryzuje się małą heterogenicznością, włączone badania wykazały umiarkowane ryzyko błędu systematycznego, a ich jakość była niska lub umiarkowana. Konieczne są przyszłe badania posiadające odpowiednią wiarygodność wewnętrzną i zewnętrzną. W przyszłości rozbieżność strzałkowa i metody oceny relacji między szczęką górną i dolną powinny być dokładniejsze.

Jeśli chodzi o nowe pomiary cefalometryczne w celu określenia rozbieżności w wymiarze pionowym w postaci kąta R, płaszczyzny zewnątrzustnej KR oraz płaszczyzny górnej granicy łuku jarzmowego, liczba przeprowadzonych badań jest ograniczona, o bardzo niskiej jakości i umiarkowanym ryzyku stronniczości badania. Jednocześnie przegląd ujawnił istnienie nowych parametrów alternatywnych do współczesnych pomiarów w badaniach 3D. Śledzenie procesu wyznaczania punktów odniesienia, linii i płaszczyzn antropometrycznych w tomografii wolumetrycznej wydaje się możliwe także w 2D. Sugestie takie wymagają jednak dalszych badań i analiz. Obecne badania nie wydają się być zbyt konstruktywne.

Publikacja 2

Wnioski wyciągnięte z przeprowadzonego przeglądu systematycznego były przyczynkiem do badań własnych skoncentrowanych na porównaniu wiarygodności i powtarzalności pomiarów cefalometrycznych odnoszących się do dyskrepancji sagitalnej porównującej pomiary kąta ANB i kąta Tau.

Wykazano, że najwyższy współczynnik korelacji Pearsona występuje w przypadku współrzędnych Ax i Ay. Błąd Dahlberga wahał się od 0,265 do 0,665, a współczynniki korelacji międzyklasowej i wewnątrzklasowej (ICC) mieściły się w przedziale od 0,841 do 1,000, wskazując na bardzo dużą zgodność pomiarów badaczy. Błąd powtarzalności (BP), błąd odtwarzalności wśród różnych lekarzy (BO), zmienność indywidualna pacjenta (ZI) oraz łączny błąd powtarzalności i odtwarzalności (R&R) wyniosły, odpowiednio: 1,61%, 0,92%, 97,47% oraz 2,53%. W przypadku kąta tau najwyższy współczynnik korelacji Pearsona stwierdzono w przypadku współrzędnych poziomych Tx i Mx. Błąd Dahlberga wahał się od 0,891 do 1,639, a wartości ICC mieściły się w przedziale od 0,147 do 0,624, wskazując na słabą zgodność pomiarów badaczy. Wartości BP, BO, Zi oraz R&R wyniosły, odpowiednio: 4,30%, 3,94%, 91,76% oraz 8,24%. Prawie cała zmienność wyników pomiarów kąta ANB i tau wynikała z wariancji międzygrupowej (zmienności indywidualnej pacjenta). Niska wartość R&R (poniżej 10%) oznacza, że oba kąty są dobrym parametrami diagnostycznymi wad strzałkowych. Ortodonci biorący udział w badaniu znacznie dokładniej mierzyli kąt ANB niż kąt tau: błąd Dahlberga i wartość R&R były około trzy razy większe, a wartość ICC – trzy i półkrotnie mniejsza w przypadku pomiarów kąta tau.

Wyniki te wskazują, że dyspersja poziomych współrzędnych punktów determinujących kąt ANB jest mniejsza niż w przypadku kąta tau, więc wartości kąta ANB cechują się mniejszym błędem pomiarowym niż wartości kąta tau. Wartość kappa Cohena, czyli współczynnika rzetelności zastosowanego do oceny spójności ortodontów w kwestii ustalania klasy szkieletowej wyniosła 0,778 w przypadku kąta ANB i 0,722 w przypadku kąta tau, a analiza wyniku dowiodła statystycznej istotności różnicy ($p < 0,001$). Oznacza to, że kąt ANB nadal pozostaje podstawowym parametrem do diagnozowania szkieletowych zaburzeń strzałkowych, a upowszechnienie kąta tau wymaga wcześniejszego edukowania ortodontów.

Dyskusję poświęcono interpretacji wyników, ich wpływu na planowane leczenie ortodontyczne, odniesieniu do grup etnicznych oraz możliwości zastosowania sztucznej inteligencji do analizy pomiarów cefalometrycznych.

Publikacja 3

Z uzyskanych wstępnie 3154 artykułów zakwalifikowano ostatecznie 13 publikacji i wyekstrahowano dane łącznie 580 pacjentów dotyczące płci i wieku badanych, strategii leczenia oraz zmiany inklinacji siekaczy w trakcie leczenia ortodontycznego.

Wyniki badań i ich istotną wartość statystyczną przed stawiono poniżej, w gradacji od badania o największej do najmniejszej istotności statystycznej (tab. 4): 1. Al-Imam i wsp. (18) wykazali, że kortykotomia podczas cofania siekaczy zmniejsza ich przechylanie średnio o 1,5° w porównaniu z brakiem retrakcji wspomaganej chirurgicznie; 2. Al-Sibaie i wsp. (16) wykazali, że cofanie zębów przed nich en-masse przy użyciu TISAD powoduje przechylanie siekaczy średnio o 2,9° mniejsze w porównaniu do tradycyjnego 2-etapowego procesu; 3. Sadek i wsp. (10) wykazali, że retrakcja en-masse przy użyciu mikroimplantów i łuków po stronie przedsionkowej powoduje zmniejszenie przechylania siekaczy szczęki średnio o 5,85° w porównaniu z takim samym przesunięciem en-masse z dostępu językowego i mikro implantów umieszczonych na podniebieniu; 4. Chen i wsp. (2) wykazali, że u pacjentów leczonych systemem PASS przechylenie siekacza szczęki było średnio o 4,8° mniejsze niż u pacjentów leczonych syste mem MBT; 5. Zhao i wsp. (12) wykazali, że użycie śródszczękowych wyciągów elastycznych podczas cofania siekaczy powoduje prze chylanie zębów przednich szczęki średnio o 7,14° mniejsze w porównaniu z zastosowaniem łańcuszków elastycznych; 6. Davoody i wsp. (15) wykazali, że tradycyjna dwuetapowa retrakcja z użyciem dodatkowego łuku intruzyjnego skutkuje przechyleniem siekaczy szczęki średnio o 8° mniejszym w porównaniu z retrakcją en-masse wspomaganą przez TISAD.

We wszystkich badaniach podczas wykonywania ruchu cofania na siekaczach występowało przechylanie, tj. występował przedsionkowy tork korzenia. Średnia wartość zmiany policzkowo-podniebiennego nachylenia korzenia w ba danych grupach wyniosła 10,46°. Największą zmianę torku siekaczy (19,13°) opisali Lee i wsp. w grupie, w której zastosowano miniimplanty ortodontyczne. Zupełnie inne wyniki uzyskali Sadeka i wsp., którzy po zastosowaniu miniimplantów po stronie przedsionkowej do cofania zębów przednich stwierdzili najmniejszą zmianę nachylenia korzeni zębów przednich w kierunku przedsionkowo-podniebiennym: 4,41°. Po uwzględnieniu wszystkich badań średnia różnica w zmianie nachylenia górnych siekaczy pomiędzy grupą kontrolną a badaną wyniosła 2,46°, co było statystycznie istotne ($p = 0,0003$). Największą rozbieżność między grupami zaobserwowano w badaniu Davoody'ego i wsp., natomiast w badaniu Deepaka i wsp. nie zaobserwowano żadnych rozbieżności między grupami.

Publikacja 4

Z uzyskanych wstępnie 1401 artykułów zakwalifikowano ostatecznie 7 publikacji i wyekstrahowano dane łącznie 284 pacjentów dotyczące płci i wieku badanych oraz zmian w

objętości wyrostka zębodołowego szczęki po leczeniu ortodontycznym z zastosowaniem retrakcji siekaczy po ekstrakcji pierwszych górnych przedtrzonowców.
W efekcie we wszystkich badaniach podczas retrakcji na siekaczach występowała resorpcja kości szczęki po stronie podniebiennej. Największą resorpcję zaobserwowano w grupie retrakcyjnej dorosłych po stronie podniebiennej w badaniach Zheng (-1.59)

Wyniki badań istotnych statystycznie przedstawiono poniżej:
Zhengi wsp wykazali resorpcję kości po stronie podniebiennej zarówno w grupie retrakcyjnej dorosłych (średnio -1,46) jak i u nastolatków (średnio -0,64), natomiast resorpcja ta była znacznie większa u dorosłych. Ponadto pomimo wzrostu grubości kości po stronie przedsionkowej u obu grup, wzrost ten był mniejszy u dorosłych (średnio +0,17) niż u nastolatków (średnio 0,33)
Hung i wsp wykazali resorpcję po stronie podniebiennej (średnio -0,94) i przyrost grubości kości po stronie przedsionkowej (średnio 0,55), jednakże nie zauważyli zmian w całkowitej grubości kości wyrostka przed i po leczeniu ortodontycznym (średnio -0,27). Dodatkowo zauważyli istotną redukcję kości zarówno w wymiarze pionowym jak i poziomym od strony podniebiennej.
Zhang Ch.i wsp wykazali resorpcję kości wyrostka zarówno po stronie przedsionkowej na wszystkich poziomach (średnio -0,35) jak i podniebiennej ale na poziomie środkowym (średnio -0,35). Nie zauważyli jakiejkolwiek różnicy zmian w zależności od płci, wieku czy trwania leczenia ortodontycznego.
Eksiwong i wsp. Zauważyli, że po stronie przedsionkowej remodeling polegający na resorpcji kości w stosunku do wielkości ruchu zęba wynosi 1:1, natomiast po stronie podniebiennej 0,2-0,4. Kość po stronie podniebiennej wydaje się nie zmieniać , a zmienia się jedynie dystans pomiędzy korzeniem a blaszką zbitą podniebienną. Natomiast inklinacja korzenia siekaczy jest jedynym czynnikiem wpływającym na zmianę objętości kości.
Zhang F. i wsp wykazali istotne zmiany w kształcie i grubości kości wyrostka zębodołowego po retrakcji siekaczy. Wyrostek staje się grubszy po stronie przedsionkowej z wyjątkiem poziomu 1. Przy czym po stronie podniebiennej następuje resorpcja kości (średnio -1,09)
Mao i wsp. Zauważyli, ze po stronie przedsionkowej zachodzi przyrost kości wyrostka po retrakcji lub nie ulega ona zmianom (średnio 0,1), przy jednoczesnej resorpcji kości na wszystkich poziomach od strony podniebiennej (średnio -0,6) oraz zmniejszeniu jej wysokości pomiędzy poziomem T0 a T1 oraz największej resorpcji kości na poziomie crestal od strony podniebiennej (średnio -0,9) Wykazali korelacje pomiędzy przemieszczeniem wierzchołka korzenia siekacza a resorpcja kości od strony podniebiennej.

Wang i wsp nie zauważyli zmian w grubości kości po stronie przedsionkowej (średnio 0,1), natomiast od strony podniebiennej wykazali istotne zmniejszenie grubości wyrostka (średnio -0,7). Przy czym po okresie retencji 18-24 miesięcy następuje odbudowa kości na poziomie L1, przy braku jakichko0lwiek zmian na pozostałych poziomach. Dodatkowo wykazali istotne zmniejszenie wysokości wyrostka po obu stronach po leczeniu ortodontycznym, które utrzymuje się po okresie retencji.

Z przeprowadzonych badań wynika, że w wyniku retrakcji siekaczy następuje istotna statystycznie zmiana grubości kości. Po stronie podniebiennej obserwuje się znaczny ubytek kości. Zaobserwowana zmiana może zależeć zarówno od wielkości przesunięcia siekaczy, jak i zmiany ich nachylenia, a co za tym idzie, zmiany położenia wierzchołków korzeni. Zmiana ta jest znacznie większa u dorosłych niż u dorastającej młodzieży. Funkcje komórkowe pogarszają się wraz z wiekiem, co może wyjaśniać zmniejszoną zdolność do przebudowy w miarę starzenia się. Dodatkowo tempo retrakcji może skutkować większą utratą kości, ponieważ procesy naprawy mogą nie nadążać za procesami resorpcji. Zmiany w kościach strony wargowej budzą kontrowersje, gdyż wykazują zarówno zyski, jak i straty. Konieczne są dalsze badania, aby uzyskane pomiary uzależnić od innych czynników, takich jak prędkość i biomechanika retrakcji, wielkość siły ortodontycznej i wiek pacjenta.

W trakcie analizy zgromadzonych danych napotkaliśmy istotne ograniczenie uniemożliwiające przeprowadzenie wiarygodnej analizy statystycznej oraz oceny heterogeniczności. Problem ten wynikał z braku jednolitości wyników pomiędzy poszczególnymi badaniami. Różnice w metodologiach, kryteriach włączenia pacjentów, a także w sposobach pomiaru i klasyfikacji wyników były na tyle znaczące, że jakakolwiek próba syntezowania tych danych mogłaby prowadzić do błędnych wniosków. Bez spójnych i porównywalnych danych, ryzyko wypaczenia wyników analizy statystycznej znacząco wzrasta, co w konsekwencji może wpływać na wiarygodność i wartość naukową wyników. Wobec powyższego, zdecydowaliśmy się na oparcie naszych wniosków na jakościowej analizie dostępnych danych, akcentując przy tym potrzebę standaryzacji przyszłych badań w celu umożliwienia szczegółowych analiz porównawczych.

Dyskusję poświęcono rozważaniu czy ruch zębów odbywa się wg teorii przez kość czy z kością. Wykazano, że im większy ruch retrakcyjny korzenia, tym większe zmiany w objętości wyrostka zębodołowego. Ponadto u dzieci i młodzieży zmiany te są mniejsze, a resorpcja kości po stronie podniebiennej i przedsionkowej nie jest tak nasilona jak u pacjentów dorosłych. Nie zaobserwowano jednak, aby płeć czy czas trwania leczenia ortodontycznego miały wpływ na zmiany zachodzące w kości. Większość badań to badania retrospektywne o średniej wartości dowodowej. Badania Eksiwronga, jako badanie prospektywne, charakteryzują się jednak dużą wartością dowodową. Badania Zhenga i in. okazały się bardzo cenne i niewątpliwie pokazały, że wiek ma ogromny wpływ na zmiany objętości wyrostka zębodołowego podczas retrakcji. U dorosłych pacjentów obserwowano większą utratę masy kostnej zarówno po stronie przedsionkowej, jak i podniebiennej, niż u młodzieży. Sugeruje to, że u młodzieży ruch ortodontyczny może zgodnie z teorią odbywać się kością, natomiast u dorosłych po zakończeniu wzrostu ten sam ruch będzie odbywał się poprzez kość.

Publikacja 5

Na podstawie wcześniej przeanalizowanych publikacji zaplanowano badanie dotyczące biomechaniki retrakcji zębów szczęki w przypadkach ekstrakcyjnych i nieekstrakcyjnych za pomocą nowatorskiej metody nielinearnej analizy metodą elementów skończonych.

Aby osiągnąć założone cele, wybrano metodologię badań skupioną na analizach numerycznych, ze szczególnym uwzględnieniem metody elementów skończonych. Podejście to ułatwiło precyzyjne odtworzenie warunków we wszystkich badanych przypadkach. Zapewnienie jednolitości warunków jest niezbędne dla miarodajnej analizy porównawczej wybranych parametrów.

W tej pracy określono wartość sił retrakcyjnych mogących skutkować przekroczeniem progu naprężeń optymalnych w więzadłach ozębnej. Przedstawiono analizę naprężeń w ozębnej wykonaną metodą elementów skończonych, na nowatorskim, nielinearnym modelu szczęki, w trakcie retrakcji zębów górnych. W badaniu jako zmienne badane uwzględniono retrakcję en masse segmentu zębów górnych przednich do miniimplantu (TISAD) umieszczonego w okolicy pomiędzy drugim zębem przedtrzonowym a pierwszym trzonowym oraz dystalizację całego łuku również do TISAD przeprowadzoną na łuku 0.017*0.025 SS w zamkach slotu 0.018, z uwzględnieniem różnych wartości sił i wysokości haczyków wpływających na wektor zastosowanej siły.

Wartości ciśnienia z uwzględnieniem mapy rozkładu powstającego w PDL w trakcie retrakcji en masse z użyciem TISAD po ekstrakcji pierwszych przedtrzonowców w slocie 0.018 na łuku 17*25 SS z zastosowaniem różnej wysokości haczyków oraz różnej wielkości sił w zakresie zastosowanych sił od 50 g do 300 g wartości ciśnienia dla całego łuku zębowego wynoszą od 0,37 kPa do 2,5 kPa. Wartości ciśnienia rosną liniowo wraz ze wzrostem zastosowanej siły. Natomiast różnice na poziomie jednej wartości siły przy różnych wysokościach haczyków są minimalne (nieistotne klinicznie), przy czym wszędzie w każdej z opisanych sytuacji najmniejsze ciśnienie występuje dla haczyka o wysokości 6mm, a największe dla haczyka o wysokości 2mm.

Ciśnienie w ozębnej siekaczy przyśrodkowych wynosi od 0,23 kPa do 1,54 kPa i również rozkładają się w liniowo w zależności od przyłożonej siły. W przeciwieństwie do całego łuku najmniejsze wartości odnotowywane są przy najniższym haczyku o wysokości 2mm i rosna wraz ze wzrostem wysokości haczyka. We wszystkich przypadkach wartości ciśnienia dla siekaczy przyśrodkowych stanowią ok 55 % wartości ciśnienia w ozębnej całego łuku. Ciśnienie w ozębnej siekaczy bocznych stanowi ok 45% wartości ciśnienia pełnego łuku i wynosi od 0,18 kPa do 1,14 kPa z zachowaniem rozkładu liniowego. W przeciwieństwie do całego łuku i siekaczy przyśrodkowych najmniejsze wartości odnotowywane są przy najwyższym haczyku wysokości 10 mm i rosną wraz ze spadkiem wysokości haczyka. W przypadku kłów wartości ciśnienia są największe i stanowią ok 75% wartości dla całego ciśnienia w PDL pełnego łuku. Jego wartości rozkładają się w zakresie 0,28 – 1,83 kPa. Zależności są równoważne w przypadku siekaczy bocznych.

Prowadząc analizę porównawczą wartości ciśnienie w PDL zarówno całego łuku jak i poszczególnych zębów mapa rozkładu nie zmienia się bez względu na zastosowaną siłę ani wysokość haczyka a co za tym idzie jest stałe bez względu na zastosowany wektor siły. Różnią się tylko proporcjonalnie wartości. Na siekaczach przyśrodkowych największe wartości lokalizują się na ścianie podniebiennej, przy czym kumulacja występuje w dolnej połowie we wszystkich przypadkach, a 1/3 przywierzchołkowa korzeni jest w strefie ciśnienia neutralnego wyjątkiem małych punków na wierzchołkach, które koncentrują większe ciśnienia. Można zauważyć ogólnie większe wartości dla siekacza prawego niż lewego. Korzenie siekaczy bocznych całą siłę kumulują w okolicy przyszyjkowej na ścianie dystalnopodniebiennej oraz punktowo na wierzchołku, natomiast pozostała część korzeni jest w strefie ciśnienia neutralnego. Natomiast kły w przeważającym obszarze znajdują się w strefie neutralnej pojedynczym miejscem akumulacji ciśnienia w okolicy przyszyjkowej ściany podniebiennej. Krytyczna wartość 4,7 kPa jest przekroczona dla pełnego łuku zębowego przy sile rzędu 600 g i koncentruje się na korzeniach górnych pierwszych trzonowców osiągając w tym samym czasie na przednim segmencie 3,88 kPa, które kumulują się głownie na siekaczu przyśrodkowym prawym w okolicy dolnej połowy podniebiennej ściany korzenia.

Wartości ciśnienia z uwzględnieniem mapy rozkładu powstającego w PDL w trakcie dystalizacji całego łuku zębowego z użyciem TISAD po ekstrakcji pierwszych przedtrzonowców w slocie 0.018 na łuku 17*25 SS z zastosowaniem różnej wysokości haczyków oraz różnej wielkości sił w zakresie zastosowanych sił od 50 g do 300 g wartości ciśnienia dla całego łuku zębowego są bardzo podobne i wynoszą od 0,33 kPa do 2,4 kPa. Wartości ciśnienia rosną również liniowo wraz ze wzrostem zastosowanej siły. Natomiast różnice na poziomie jednej wartości siły przy różnych wysokościach haczyków są jeszcze bardziej minimalne. Wartości ciśnienia są wszędzie odpowiednio o ok 9-10% mniejsze. Natomiast mapa rozkładu ciśnienia jest taka sama we wszystkich przypadkach.

Wykazano zatem , że optymalnie łuki 0,017*0,025 SS w zamkach MBT 0,018 zapewniają doskonałą kontrolę torku, prowadząc do precyzyjnego osiowego przemieszczenia zębów, przy zastosowaniu optymalnych sił 180-200g/stronę nie ma ryzyka resorpcji wierzchołka korzenia.

Dyskusję poświęcono roli kontroli torku w zapobieganiu resorpcjom korzeni oraz wartości i znaczenia wysokiej jakości modeli nieliniowych w analizie ciśnienia hydrostatycznego w PDL w trakcie ruchu ortodontycznego.

Publikacja 6

Z uzyskanych wstępnie 1862 artykułów zakwalifikowano ostatecznie 6 publikacji i wyekstrahowano dane łącznie 164 pacjentów dotyczące płci i wieku badanych oraz obecności resorpcji w wyniku kontaktu z blaszką zbitą kanału przysiecznego.

We wszystkich artykułach skrócenie korzeni siekaczy górnych po retrakcji było statystycznie większe w przypadku kontaktu z kanałem przysiecznym:

Yu i wsp wykazali większą resorpcję korzeni w grupie retrakcyjnej (2.3±1.40mm) niż w kontrolnej(1.1±0.75mm). Dodatkowo utworzono podgrupy ze względu na odległość korzeni do IC po leczeniu (separation, approximation, contact, invasion). Im korzeń siekacza był bliżej kanału przysiecznego, tym większa była resoprcja, jednak ten wynik nie był istotny statystycznie. W grupie retrakcyjnej doszło 4 razy częściej do inwazji lub kontaktu korzeni z kanałem przysiecznym w porównaniu z grupą kontrolną. W 11,4% w grupie retrakcyjnej doszło do zmiany przebiegu kanału przysiecznego co może świadczyć o jego zdolności do remodelingu.

Chung i wsp wykazali, że w 53% przypadków leczenia retrakcyjnego doszło do inwazji kanału przysiecznego przez korzenie siekaczy. Wykazano wyższe ryzyko kontaktu korzeni z kanałem, gdy odległość międzykorzeniowa jest mniejsza niż szerokość kanału przysiecznego. W podgrupie, w której występowała inwazja, resorpcja była statystycznie większa(2,4±1,59 mm) niż w grupie nieinwazyjnej(0,8±0,96mm)P<.0001. Pacjenci z inwazją, u których doszło do remodelingu(1±0,92mm) charakteryzowali się mniejszą resorpcją niż pacjenci bez remodelingu(3,3±1,54mm)P<.0001.

Pan i wsp. wykazali zdecydowanie większe skrócenie(2.63±0.93) korzeni siekaczy w grupie kontaktu korzeni z kanałem przysiecznym niż w grupie bez kontaktu(1.14±0.83), co może wykazywać na ich pozytywną korelację. W przypadku niekontrolowanego przechylania siekaczy istnieje zwiększone ryzyko inwazji kanału w rejonie przyszyjkowym. Ryzyko kontaktu korzeni zwiększa się w przypadku niskiej pozycji kanału przysiecznego.

Nakada i wsp. Wykazał że resorpcja korzeni była statystycznie większa po stronie bliższej w stosunku do kanału przysiecznego niż przeciwległej. Dodatkowo zakres resorpcji podniebiennej po stronie bliższej(2,49±0,61) kanału był również większy niż po stronie dalszej(1,51±0,49mm). Finalnie uznał, że bliskość wierzchołka do blaszki zbitej IC jest czynnikiem wpływającym na resorpcję korzenia.

Imamura i wsp. opisali przypadek kliniczny pacjentki, u której po retrakcji siekaczy korzeń tego, który był w kontakcie z kanałem przysiecznym uległ resorpcji na powierzchni kontaktu(3,6mm). W związku z tym uznano, że rozmiar i morfologia IC ma wpływ na resoprcję korzeni.

Chung i wsp również opisali przypadek resorpcji korzenia po kontakcie z IC z zachowaniem żywotności zęba.

Wartość statystyczna Q wyniosła 36,25 przy p = 0,0003 i I2 = 66,9%. Dane te wskazują na wysoki poziom niejednorodności badań. Wynika to najprawdopodobniej z różnych technik ortodontycznych stosowanych w poszczególnych badaniach. Dodatkowo przeprowadzono analizę heterogeniczności badań włączonych do metaanalizy. W tym celu przeprowadzono test niejednorodności oparty na Q i I2.

W tracie dyskusji poruszono temat zastosowania obrazowania 3D i uwidocznienia kanału przysiecznego oraz istoty jego morfologii, kształtu, przebiegu na związek z resorpcją korzeni siekaczy występującą po ich retrakcji. Istnieje dość ograniczona liczba badań, z czego wszystkie są badaniami retrospektywnymi, dotyczącymi zmiany w długości korzeni siekaczy w związku z kontaktem z IC. W systematic review wszystkie z nich wykazały pozytywny związek pomiędzy stopniem resorpcji a zmniejszeniem odległości korzeni do IC. Dodatkowo badania Yu i wsp. dowiodły zdolności do remodelingu kanału w odpowiedzi na ortodontyczny ruch zębów, czemu towarzyszył mniejszy stopień resorpcji. U 11,4% pacjentów po retrakcji zaobserwowano zmianę kierunku przebiegu kanału ze skośno-prostego na skośno-zakrzywiony. Konieczne są kolejne badania, które być może uzależniłyby zdolność IC do remodelingu od zastosowanej siły, czasu przesunięć zębowych lub innych czynników ortodontycznych, co mogłoby zmniejszyć ilość powikłań w postaci resorpcji korzeni.

Publikacja 7

Wnioski wyciągnięte z przeprowadzonego przeglądu systematycznego były powodem do zaplanowania badań własnych ukierunkowanych na analizę zależności anatomii kanału przysiecznego z płcią i wiekiem pacjentów oraz w celu opracowania grup ryzyka.

W badaniu wykorzystano dokumentację CBCT wiązki stożkowej znajdujące się w zasobach Katedry Ortopedii Szczękowej i Ortodoncji Uniwersytetu Medycznego im. Piastów Śląskich we Wrocławiu. W badaniu wykorzystano CBCT wiązki stożkowej 67 pacjentów (35 kobiet, 32 mężczyzn;) w wieku 13-49,

W diagnostyce ortodontycznej wykorzystano skany CBCT wykonane w latach 2017-2021 przed leczeniem ortodontycznym. Kryteriami włączenia dokumentacji CBCT pacjenta do grupy badanej były: (1) Całkowity rozwój korzeni siekaczy górnych. (2) Wyraźnie widoczna szczęka. (3) Pacjenci z uzębieniem stałym. (4) Bez historii leczenia ortodontycznego. (5) Pacjenci ogólnie zdrowi, bez chorób kości w wywiadzie. Kryteria wyłączenia: (1) Brakujące siekacze szczęki. (2) Patologia siekaczy szczęki. (3) Anomalie rozwojowe kanału siecznego (dodatkowe kanały w okolicy kanału siecznego oraz wyraźne asymetrie). (4) Niska jakość CBCT uniemożliwiająca dokładne pomiary. (5) Obecność artefaktów obrazowych utrudniających pomiary w odcinku przednim szczęki. (6) Niekompletny rozwój korzeni. (7) Resorpcja korzeni na skutek urazu lub stanu zapalnego. (8) Historia dotychczasowego leczenia ortodontycznego.

Po wyłonieniu grupy badanej uczestników zakwalifikowano do grup ze względu na płeć i wiek. Utworzono następujące 4 grupy wiekowe: 13-20 lat, 21-29 lat, 30-39 lat, 40-49 lat.

Pomiary zostały dokonane przez dwóch badaczy niezależnie od siebie i średnia ich wyników stanowiła dane użyte w analizie statystycznej.

Wykonane zostały następujące pomiary:

na przekrojach horyzontalnych oddzielnie dla każdego poziomu – L1, L2 i L3:

- Szerokość kanału przysiecznego - |Cl-Cl|
- Wymiar przednio-tylny IC - |Ca-Cp|
- Pomiar odległości pomiędzy najbardziej mezjalnym punktem na korzeniu i styczną przechodzącą przez najbardziej doprzedni punkt kanału przysiecznego - |Rm-Cat|
- Pomiar odległości od punktu Cl do tylnej krawędzi korzenia siekacza - |Cl-Rpt|
- Pomiar odległości międzykorzeniowej - |Rm-Rm| na przekrojach strzałkowych:
- Kąt utworzony przez długą oś korzenia siekacza i płaszczyznę podniebienną

- Kąt utworzony przez długą oś kanału przysiecznego i płaszczyznę podniebienną

na przekrojach czołowych:

- Kąt utworzony przez długie osie siekaczy przyśrodkowych (wartość powyżej zera - korzenie zbieżnie, wartości ujemne - rozbieżne)

Badanie korelacji dotyczącej wpływu szerokości kanału na długość wykazało zróżnicowane wyniki. Biorąc pod uwagę całą grupę pacjentów na poziomie L1 ta korelacja była istotna statystycznie (p=0,0017) ale przeciętna (r=0,3757) i wykazywała wzrost długości kanału wraz ze wzrostem szerokości. W grupie samych mężczyzn ta korelacja okazała się wysoka (r=0,557390, p=0,0009), podczas gdy okazała się słaba i nieistotna statystycznie w grupie kobiet (r=0,15035;p=0,39). Na poziomie L2 korelacja zarówno u wszystkich pacjentów jak i z podziałem na płeć jest dodatnia i wysoka (r=0,68736, p<0,05; r=0,7527, p<0,05; r=0,62191, p<0,05). Na poziomie L3 również utrzymuje się dodatnia korelacja na poziomie wysokim i bardzo wysokim u wszystkich pacjentów oraz we wszystkich grupach wiekowych zarówno u mężczyzn (r=0,72893, p<0,05) jak i u kobiet (r=0,65578, p<0,05).

W przeprowadzonych badaniach szerokość kanału na poziomie L1 była zbliżona zarówno w grupie mężczyzn jak i w grupie kobiet natomiast znacznie i istotnie statystycznie (p<0,05) różniła się tutaj długość kanału i była większa u mężczyzn niż u kobiet. Na poziomie L2 wartości zarówno szerokości jak i długości były zbliżone w grupie kobiet i mężczyzn, na poziomie L3 szerokość nadal była zbliżona natomiast długość różniła się już znacząco i była mniejsza u mężczyzn niż u kobiet. W podziale na grupy wiekowe wysokie zróżnicowanie występowało w grupie od 21 do 29 lat , której na poziomie L1 długość kanału była zdecydowanie większa u mężczyzn niż u kobiet podobnie jak w grupie 30-39 lat oraz 40-49 lat. Na pozostałych poziomach i w pozostałych grupach wartości były zbliżone.

Angulacja siekaczy przyśrodkowych szczęki nie koreluje z szerokością kanału analizując pełną grupę lub tylko płeć. Brak korelacji jest istotny statystycznie. Natomiast wykazuje wysoką korelację na poziomie L1 zarówno w grupie kobiet jak i mężczyzn w wieku 13 - 20 lat. W grupie kobiet ta korelacja jest ujemna (r= - 0,6172) co oznacza że wraz ze wzrostem szerokości kanału zwiększa się odległość międzywierzchołkowa, natomiast w przypadku mężczyzn (r=0,64045) ta korelacja jest dodatnia czyli odwrotnie im szerszy kanał tym bardziej zbieżne są korzenie. Wysoka pozytywna korelacja utrzymuje się w grupie mężczyzn do 30 roku życia. U pacjentów w wieku 30-39 lat wykazuje ujemną korelacje o wysokiej sile. U kobiet wysoka negatywna korelacja występuje do 40 roku życia. W wieku od 21 do 40 lat korelacja jest również ujemna ale wykazuje mniejszą siłę. Korelacje w grupach wiekowych nie wykazują istotności statystycznej. Na poziomie L2 korelacje są różnej mocy a tendencja zarówno u mężczyzn jak i u kobiet utrzymuje się podobnie jak na poziomie L1. Wyjątek stanowi grupa mężczyzn w wieku 30-39 lat gdzie w przeciwieństwie do innych męskich grup korelacja jest wysoka i ujemna.(r=-0,5463) ale nieistotna statystycznie. Na poziomie L3 korelacje nie występują.

Pozytywną bardzo wysoką korelację pomiędzy inklinacją siekaczy a inklinacją kanału zauważyć można w grupie kobiet od 13 do 20 lat (r=0,828, p<0,05) i od 40 do 49 lat (r=0,603). W przypadku mężczyzn przeciętną i ujemną korelację obserwuje się pomiędzy 13 -20 oraz 30-39 rokiem życia (r= -0,4295; r= -0,495;p>0,05). Wysoką, dodatnią oraz istotną statystycznie korelację uzyskano w przedziale 20-29 lat (r=0,8682, p<0,05). W ogólnym podziale na płeć tylko kobiety wykazują istotną statystycznie ale przeciętną korelację między tymi parametrami. Zależność między szerokością kanału a odległością między najbardziej mezjalnym punktem na korzeniu oraz styczną przechodzącą przez najbardziej doprzedni punkt kanału przysiecznego jest obserwowana jedynie w grupie mężczyzn i ma wartość ujemną we wszystkich grupach wiekowych. Wskazuje to, że im szerszy kanał tym bliżej blaszki zbitej kanału przysiecznego znajdują się korzenie. U kobiet wysoka i pozytywna korelacja na poziomie L1 i L3 występuje jedynie w wieku 40-49 lat. (r=0,6775; p<0,05;r=0,6628). Oznacza to, że im węższy kanał tym korzenie są zlokalizowane bliżej kanału.

W odniesieniu do szerokości kanału nie zaobserwowano istotnej zależności pomiędzy grupą kobiet i mężczyzn. Można jedynie obserwować tendencję do zwiększania się szerokości kanału z wiekiem u kobiet na wszystkich poziomach. Długość kanału jest zdecydowanie mniejsza u kobiet niż u mężczyzn na poziomie L1, Wyrównuje się na poziomie L2 i jest zdecydowanie większa na poziomie L3. Wykazuje ona największe rozbieżności w wynikach na wszystkich poziomach w najmłodszej grupie 13-20 badanych zarówno u kobiet jak i u mężczyzn. Charakterystyczne jest zmniejszanie się długości kanału u kobiet do 39 roku życia i ponowny wzrost po 40 roku życia ma poziomie L1. U mężczyzn długość kanału na tym poziomie jest podobna we wszystkich grupach wiekowych. U kobiet na poziomie L3 obserwujemy wzrost wymiaru przednio tylnego kanału wraz z wiekiem, podczas gdy u mężczyzn pozostaje na podobnym lub nieznacznie zwiększonym poziomie. Żadne z wyników nie były istotne statystycznie (p>0,05).

Zaobserwowano, że u kobiet inklinacja siekaczy względem podstawy szczęki maleje z wiekiem do 40 roku życia, po czym zaczyna wzrastać w przeciwieństwie do mężczyzn u których z wiekiem inklinacja siekaczy rośnie ale bez istotnego poziomu statystycznego.

Badania CBCT wykazały ujemną korelację w grupie młodych mężczyzn w wieku 13-20 lat (r= -0,9303 p<0,05,) na wszystkich poziomach pomiędzy angulacją korzeni siekaczy przyśrodkowych szczęki a odległością między najbardziej mezjalnym punktem na korzeniu oraz styczną przechodzącą przez najbardziej dopoprzedni punkt kanału. Można przyjąć że im bardziej zbieżnie są ustawione korzenie tym odległość do kanału jest mniejsza. Podczas gdy u kobiet podobna korelacja występuje dopiero w wieku 40 - 49 lat. (r= -0,5544) i jest nieistotna statystycznie.

W dyskusji zauważono, że znając ryzyko powikłań związanych z budową anatomiczną kanału przysiecznego może się okazać że w pewnej populacji pacjentów niezbędny będzie kompromis ortodontyczny tak, aby ochronić korzenie i aparat przyzębia, a nie dążenie do uzyskania cefalometrycznych norm. Dotychczasowe badania skupiały się głównie na analizie kształtu kanału, jego długości w wymiarze od jamy nosowej do jamy ustnej, średniej średnicy kanału, powiązania tych parametrów z wiekiem, płcią lub typem wady szkieletowej czy kierunkiem wzrostu twarzy.

Na podstawie uzyskanych wyników stworzono grupy ryzyka pacjentów w odniesieniu do płci, wieku i ruchów ortodontycznych oraz do anatomii kanału przysiecznego:

Czynnik ryzyka	Grupa ryzyka
Szerokość kanału przysiecznego	Mężczyźni
Przednio tylna długość kanału	Mężczyźni – przyszyjkowo (nadmierne przechylanie siekaczy) Kobiety – wierzchołkowo (ruch osiowy,torkowanie i wychylanie) Kobiety po 40 rż – przechylanie, torkowanie i retrakcja zwłaszcza po osteodystrakcji
Angulacja korzeni siekaczy przyśrodkowych szczęki (zbieżne/rozbieżne)	Mężczyźni w wieku 13-30 lat (ruch osiowy, nadmierne torkowanie i wychylanie)
Inklinacja kanału a inklinacja siekaczy	Wiek 13-20 Kobiety – przyszyjkowo (przechylanie, nadmierna retrakcja) Mężczyźni – wierzchołkowo (wychylanie, torkowanie oraz ruch osiowy)
Szerokość kanału a odległość korzeni od kanału	Mężczyźni – przyszyjkowo (przechylanie, nadmierna retrakcja) Mężczyźni 13-20 – poziom L2 (ruch osiowy) Kobiety po 40 rż – przyszyjkowo i wierzchołkowo (wszystkie ruchy)

10. Wnioski

1. Analiza porównawcza kąta ANB i kąta Tau w ocenie dyskrepancji sagitalnej potwierdziła, że kąt ANB nadal pozostaje podstawowym parametrem do diagnozowania szkieletowych zaburzeń strzałkowych, a upowszechnienie kąta tau wymaga wcześniejszego edukowania ortodontów. Powtarzalność oznaczania punktów pomiarowych oraz ocena indywidualnej koperty kostnej ma istotne znaczenie w aspekcie prawidłowej diagnostyki i doboru metody leczenia. Błąd ludzki może wpłynąć na sam proces pomiaru oraz na jego interpretację. W celu największej wiarygodności należy zidentyfikować najbardziej stabilne i powtarzalne punkty antropometryczne, niezależnie od kierunku wzrostu i zastosowanego leczenia ortodontycznego. Warto jednak pamiętać, że żadna metoda nie jest całkowicie wolna od błędów, a w niektórych sytuacjach uzyskane wyniki mogą wymagać walidacji metodą alternatywną. Badania skupiające się na analizie cefalometrycznej zazwyczaj koncentrują się na jednej grupie etniczne, co może prowadzić do błędnej interpretacji wyników. Zaś powtarzalność, oceniająca stopień w jakim pomiary wykonywane przez tego samego operatora pokrywają się, i odtwarzalność, oceniająca pomiary wykonywane przez rożnych operatorów, mają kluczowe znaczenie dla dokładnej oceny zależności pomiędzy podstawą szczęki, wyrostkami zębodołowymi i zębami w zarówno w wymiarze strzałkowym, jak i pionowym. W przypadku nowego nieznanego i niewykonywanego dotychczas pomiaru istnieje wysokie ryzyko błędu ludzkiego. Błąd Dahlberga $p>0,1$ świadczy o konieczności nauczenia ortodontów oznaczania punktów antropometrycznych wchodzących w skład pomiaru.

2. Kontakt korzeni siekaczy z kanałem przysiecznym zwiększa ryzyko resorpcji tych korzeni. W diagnostyce ortodontycznej za pomocą obrazowania 3D należy uwzględnić anatomię układu IC, a ryzyko powikłań resorpcyjnych można zmniejszyć poprzez odpowiednie zaplanowanie zakresu przemieszczenia i torku korzeni siekaczy oraz ewentualne zastosowanie zamków siecznych z wbudowanym większym kątem. Istnieje zróżnicowanie szerokości kanału siecznego w zależności od płci. Długość przednio-tylna kanału w dużej mierze zależy od jego szerokości. Nachylenie kanału jest zależne od nachylenia siekaczy w różnych grupach wiekowych. Szerokość kanału zależy od zależnego od płci położenia zbieżnego lub rozbieżnego siekaczy. Blaszka zbita, która otacza kanał przysieczny jako pierwsza

może przeszkadzać siekaczom podczas retrakcji, a także powodować ich resorpcję. Nasilone wychylenie siekaczy należy leczyć jak najwcześniej w okresie wzrostu młodzieńczego, kiedy zdolność organizmu do przebudowy jest duża i gdy wraz z kością następuje ruch ortodontyczny. W tym wieku kanał przysieczny, którego nachylenie zależne jest od nachylenia siekaczy, również może mieć większą zdolność do przebudowy. Znajomość anatomii kanału siecznego i zastosowanie obrazowania 3D u pacjentów wysokiego ryzyka może zapobiec resorpcji korzenia siekacza, uwzględniając indywidualne warunki anatomiczne pacjenta podczas planowania ortodontycznego przesuwania zębów.

3. Dwustronna kortykotomia oraz zastosowanie miniimplantów do retrakcji en masse są najlepszymi i skutecznymi metodami kontroli torku podczas retrakcji siekaczy w leczeniu ortodontycznym. Zastosowanie zarówno mechaniki przedsionkowej, jak i dodatkowej rurki w zamkach umieszczonych na zębach trzonowych, co pozwala uzyskać efekt podobny do łuku intruzyjnego, badano w protokołach o niejasnym ryzyku błędu systematycznego, w których różne czynniki mogły mieć wpływ na wiarygodność wyników. Wiek pacjenta wydaje się nie mieć znaczenia dla kontroli torku. W wyniku retrakcji siekaczy następuje znaczna utrata kości, co zmniejsza odległość między powierzchnią kości a powierzchnią korzenia od strony podniebiennej. Wielkość tej zmiany może być różna, w zależności od stopnia przemieszczenia siekaczy i zmian w ich nachyleniu, co wpływa na położenie wierzchołków korzeni. Zmiana ta jest znacznie większa u dorosłych niż u dorastającej młodzieży. Uzasadnieniem tego twierdzenia jest powszechnie znane zjawisko spadku aktywności komórkowej wraz z wiekiem. Zmniejszenie szybkości i intensywności zmian komórkowych może wyjaśniać zmniejszoną zdolność do przebudowy wraz ze wzrostem wieku pacjenta. Ruch ortodontyczny u dorosłych odbywa się poprzez kość i najczęściej kość nie dostosowuje się do nowego położenia zębów. Blaszkę korową podniebienną należy traktować jako nieuszkodzoną ścianę ograniczającą zakres planowanego ruchu siekaczy. Łuki 0,017*0,025 SS w zamkach MBT 0,018 zapewniają doskonałą kontrolę torku, prowadząc do precyzyjnego osiowego przemieszczenia zębów, przy zastosowaniu optymalnych sił 180-200g/stronę nie ma ryzyka resorpcji wierzchołka korzenia dzięki równomiernemu rozłożeniu lekkiego i średniego ciśnienia hydrostatycznego σh w więzadle przyzębia (PDL). Przyłożenie potrójnych sił ortodontycznych (600-640 g/stronę) może zainicjować proces resorpcji poprzez zamknięcie naczyń

włosowatych, natomiast próba wyrównania łuku zębowego przy znacznej rozbieżności zębowo-wyrostkowej może skutkować fenestracją płytki przedsionkowej wyrostka zębodołowego. Zaleca się stosowanie wysokiej jakości modeli nieliniowych do analizy elementów skończonych (FEA), aby zapewnić wiarygodne, porównywalne i realistyczne symulacje bardzo przypominające warunki w jamie ustnej.

11. Piśmiennictwo

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12. Spis rycin

Publikacja 7

12. Spis tabel

Publikacja 6

Tabela 1 - str. 144

Publikacja 7

Tabela 1 - str. 158

Tabela 2,3 - str. 159

Tabela 4,5 - str. 160

Tabela 6 - 167

14.1. Zgody Komisji Bioetycznej

KOMISJA BIOETYCZNA

Komisja Bioetyczna
przy Okręgowej Radzie Lekarskiej w Zielonej Górze
65-735 Zielona Góra, ul. Batorego 71
tel. (068) 320 79 00, fax (068) 3207815

Uchwała Komisji Bioetycznej Nr 01/173/2023

z dnia 06 marca 2023 r.

w sprawie wydania opinii o badaniu naukowym pt.: **„Wpływ ekspansji szczęki na struktury anatomiczne w okolicy siekaczy górnych – analiza możliwości zmniejszenia powikłań w postaci resorpcji siekaczy po leczeniu ortodontycznym w wyniku poszerzonej diagnostyki CBCT"**.

Opinia wydana jest na podstawie art. 29 ust. 2 ustawy z dnia 16 grudnia 2016 r. o zawodach lekarza i lekarza dentysty (Dz.U. 2020 poz. 514 t.j.), rozporządzenia Ministra Zdrowia i Opieki Społecznej (z dnia 11 maja 1999 r. w sprawie szczegółowych zasad powoływania i finansowania oraz trybu działania komisji bioetycznych (Dz.U. Nr 47, poz. 480 z 1999 r.) oraz uchwały nr 49/VIII/2019 Okręgowej Rady Lekarskiej w Zielonej Górze z dnia 25 kwietnia 2019 r. w sprawie powołania Komisji Bioetycznej.

Komisja Bioetyczna przy Okręgowej Izbie Lekarskiej w Zielonej Górze na posiedzeniu w dniu **06 marca 2023 r**. zapoznała się ze zgłoszeniem badania naukowego zatytułowanego **„Wpływ ekspansji szczęki na struktury anatomiczne w okolicy siekaczy górnych – analiza możliwości zmniejszenia powikłań w postaci resorpcji siekaczy po leczeniu ortodontycznym w wyniku poszerzonej diagnostyki CBCT"**.

Głównym wykonawcą badania naukowego jest dr n.med. Anna Ewa Kuc. Badanie będzie prowadzone w Dental Star Specjalistyczne Centrum Stomatologii Estetycznej, ul. Marii Konopnickiej, nr 1C, lok. U3, 15-215 Białystok. Kierownikiem naukowym projektu jest dr n. med. Jacek Kotula.

Do wniosku dołączono następujące dokumenty:

1. Protokół badania.
2. Informacja dla uczestnika badania, zawierająca dane o celach i zasadach przeprowadzenia eksperymentu medycznego.
3. Formularz świadomej zgody uczestnika badania i wzór oświadczenia składanego przez osobę poddaną eksperymentowi medycznemu
4. Lista odpowiedniego piśmiennictwa.
5. Życiorys naukowy badacza.
6. Zasady ubezpieczenia pacjentów

W wyniku tajnego głosowania w formie zdalnej Komisja Bioetyczna wyraża zgodę na przeprowadzenie badania klinicznego zatytułowanego:
„Wpływ ekspansji szczęki na struktury anatomiczne w okolicy siekaczy górnych – analiza możliwości zmniejszenia powikłań w postaci resorpcji siekaczy po leczeniu ortodontycznym w wyniku poszerzonej diagnostyki CBCT".

Komisja zastrzega sobie prawo do uzyskiwania **informacji raz na 6 miesięcy** o wszelkich naruszeniach warunków prowadzonego badania, w tym o: powikłaniach i efektach niepożądanych powstałych w związku z prowadzonym badaniem oraz do uzyskania raportu końcowego.

Komisja Bioetyczna rekomenduje zachowanie szczególnych zasad ostrożności oraz prowadzenie badania zgodnie z obowiązującymi przepisami prawa oraz zasadami bioetyki.

Komisja Bioetyczna przy Okręgowej Izbie Lekarskiej w Zielonej Górze działa zgodnie z zasadami Good Clinical Practice (ICH-GCP), Dyrektywą 2001/20/WE Parlamentu Europejskiego i Rady z dnia 4 kwietnia 2001 roku w sprawie zbliżania przepisów ustawowych, wykonawczych i administracyjnych Państw Członkowskich, odnoszących się do wdrożenia zasady dobrej praktyki klinicznej w prowadzeniu badań klinicznych produktów leczniczych, przeznaczonych do stosowania przez człowieka (Dz.U.UE.L.2005.91.13) oraz Dyrektywą Komisji 2005/28/WE z 8 kwietnia 2005 roku ustalająca zasady oraz szczegółowe wytyczne dobrej praktyki klinicznej w odniesieniu do badanych produktów leczniczych przeznaczonych do stosowania u ludzi, a także wymogi zatwierdzania produkcji oraz przywozu takich produktów (Dz.U.UE.L.2005.91.13), przepisami Rozporządzenia Ministra Zdrowia z dnia 2 maja 2012r. w sprawie dobrej praktyki Klinicznej (Dz.U. 2012, poz. 489) oraz przestrzega Deklaracji Helsińskiej Światowego Stowarzyszenia Lekarzy (WMA1).

Do opinii załączono wykaz osób biorących udział w głosowaniu.

PRZEWODNICZĄCY KOMISJI BIOETYCZNEJ
przy Okręgowej Radzie Lekarskiej
OIL w Zielonej Górze
lek. Dariusz Kosiński

14.2. Dorobek naukowy doktoranta

lek. dent. Anna Ewa Kuc

WYKAZ PUBLIKACJI

1. Publikacje w czasopismach naukowych

1.1 Publikacje w czasopiśmie z IF

Lp	Opis bibliograficzny	IF	Punkty
1	**Kuc Anna Ewa**, Kotuła Jacek, Nahajowski Marek, Warnecki Maciej, Lis Joanna, Amm Ellie, Kawala Beata, Sarul Michał: Methods of anterior torque control during retraction: a systematic review, Diagnostics, 2022, vol. 12, nr 7, art.1611 [18 s.], DOI:10.3390/diagnostics12071611	3,6	70
2	Kotuła Jacek, **Kuc Anna Ewa**, Lis Joanna, Kawala Beata, Sarul Michał: New sagittal and vertical cephalometric analysis methods: a systematic review, Diagnostics, 2022, vol. 12, nr 7, art.1723 [33 s.], DOI:10.3390/diagnostics12071723	3,6	70
3	**Kuc Anna Ewa**, Kotuła Jacek, Nawrocki Jakub, Szeląg Ewa, Kawala Beata, Lis Joanna, Sarul Michał: Morphological evaluation of the incisive canal in the aspect of the diagnosis and planning of orthodontic treatment - CBCT study, Applied Sciences-Basel, 2023, vol. 13, nr 21, art.12010 [17 s.], DOI:10.3390/app132112010	2,7*	100
4	**Kuc Anna Ewa**, Kotuła Jacek, Nawrocki Jakub, Babczyńska Alicja, Lis Joanna, Kawala Beata, Sarul Michał: The assessment of the rank of torque control during incisor retraction and its impact on the resorption of maxillary central incisor roots according to incisive canal anatomy - systematic review, Journal of Clinical Medicine, 2023, vol. 12, nr 8, art.2774 [13 s.], DOI:10.3390/jcm12082774	3,9*	140
5	Kotuła Jacek, **Kuc Anna**, Szeląg Ewa, Babczyńska Alicja, Lis Joanna, Matys Jacek, Kawala Beata, Sarul Michał: Comparison of diagnostic validity of cephalometric analyses of the ANB angle and Tau angle for assessment of the sagittal relationship of jaw and mandible, Journal of Clinical Medicine, 2023, vol. 12, nr 19, art.6333 [16 s.], DOI:10.3390/jcm12196333	3,9*	140
6	**Kuc Anna Ewa**, Kotuła Jacek, Nawrocki Jakub, Dobrzyński Maciej, Wiglusz Rafał J., Watras Adam, Sarul Michał, Lis Joanna, Kawala Beata: Properties and application of the gummetal wire for the treatment of an open bite—brief narrative review and case report, Applied Sciences-Basel, 2024, vol. 14, nr 7, art.2991 [15 s.], DOI:10.3390/app14072991	2,7*	100
7	**Kuc Anna Ewa**, Kotuła Jacek, Nawrocki Jakub, Kulgawczyk Maria, Kawala Beata, Lis Joanna, Sarul Michał: Bone remodeling of maxilla after retraction of incisors during orthodontic treatment with extraction of premolars based on CBCT study: a systematic review, Journal of Clinical Medicine, 2024, vol. 13, nr 5, art.1503 [14 s.], DOI:10.3390/jcm13051503	3,9*	140
8	**Kuc Anna Ewa**, Sybilski Kamil, Kotuła Jacek, Piątkowski Grzegorz, Kawala Beata, Lis Joanna, Saternus Szymon, Sarul Michał: The hydrostatic pressure distribution in the periodontal ligament and the risk of root resorption - a finite element method (FEM) study on the nonlinear innovative model, Materials, 2024, vol. 17, nr 7, art.1661 [34 s.], DOI:10.3390/ma17071661	3,4*	140
	Podsumowanie	27,7	900

**IF 2022*

1.2 Publikacje w czasopiśmie bez IF –

Impact Factor: **27,7**

Punkty ministerialne: 900,0

Signed by / Podpisano przez:
Dominika Sidorska
Date / Data: 2024-06-04 09:31

1. Streszczenia zjazdowe
   Anna Kuc, Jacek Kotuła, Michał Sarul
   Metody kontroli torku w trakcie retrakcji - przegląd systematyczny
   23 Zjazd PTO w Sopocie – 2023 r.

Całkowity lmpact factor: 27,7

Punkty ministerialne: 900

14.4. Oświadczenia o współautorstwie

Ja dr.n.med. Jacek Kotuła oświadczam, że w publikacjach:

Kotuła J, Kuc AE, Lis J, Kawala B, Sarul M. New Sagittal and Vertical Cephalometric Analysis Methods: A Systematic Review. Diagnostics. 2022; 12(7):1723.

Kotuła J, Kuc A, Szeląg E, Babczyńska A, Lis J, Matys J, Kawala B, Sarul M. Comparison of Diagnostic Validity of Cephalometric Analyses of the ANB Angle and Tau Angle for Assessment of the Sagittal Relationship of Jaw and Mandible. Journal of Clinical Medicine. 2023; 12(19):6333.

Kuc AE, Kotuła J, Nahajowski M, Warnecki M, Lis J, Amm E, Kawala B, Sarul M. Methods of Anterior Torque Control during Retraction: A Systematic Review. Diagnostics. 2022; 12(7):1611

Kuc AE, Kotuła J, Nawrocki J, Kulgawczyk M, Kawala B, Lis J, Sarul M. Bone Remodeling of Maxilla after Retraction of Incisors during Orthodontic Treatment with Extraction of Premolars Based on CBCT Study: A Systematic Review. Journal of Clinical Medicine. 2024; 13(5):1503. https://doi.org/10.3390/jcm13051503

Kuc AE, Sybilski K, Kotuła J, Piątkowski G, Kawala B, Lis J, Saternus S, Sarul M. The Hydrostatic Pressure Distribution in the Periodontal Ligament and the Risk of Root Resorption—A Finite Element Method (FEM) Study on the Nonlinear Innovative Model. Materials. 2024; 17(7):1661.

Kuc AE, Kotuła J, Nawrocki J, Babczyńska A, Lis J, Kawala B, Sarul M. The Assessment of the Rank of Torque Control during Incisor Retraction and Its Impact on the Resorption of Maxillary Central Incisor Roots According to Incisive Canal Anatomy—Systematic Review. Journal of Clinical Medicine. 2023; 12(8):2774.

Kuc AE, Kotuła J, Nawrocki J, Szeląg E, Kawala B, Lis J, Sarul M. Morphological Evaluation of the Incisive Canal in the Aspect of the Diagnosis and Planning of Orthodontic Treatment—CBCT Study. Applied Sciences. 2023; 13(21):12010

mój udział polegał na : formułowaniu problemów i hipotez badawczych, pomocy w rekrutacji uczestników badań, analizie i interpretacji wyników, przygotowaniu i korekcie manuskryptów.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

Jacek Kotuła

Digitally signed by Jacek Kotuła
Date: 2024.05.24 22:17:05 +02'00'

OŚWIADCZENIE

Ja dr inż. Kamil Sybilski oświadczam, że w publikacji:

Kuc AE, Sybilski K, Kotuła J, Piątkowski G, Kawala B, Lis J, Saternus S, Sarul M. The Hydrostatic Pressure Distribution in the Periodontal Ligament and the Risk of Root Resorption—A Finite Element Method (FEM) Study on the Nonlinear Innovative Model. Materials. 2024; 17(7):1661.

mój udział polegał na: formułowaniu problemów i hipotez badawczych, projektowaniu badań, przygotowaniu modelu FEM, analizie i interpretacji wyników, przygotowaniu i korekcie manuskryptów, przygotowaniu tabel i rycin.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

OŚWIADCZENIE

Ja mgr.tech.dent. Grzegorz Piątkowski oświadczam, że w publikacji:

Kuc AE, Sybilski K, Kotuła J, Piątkowski G, Kawala B, Lis J, Saternus S, Sarul M. The Hydrostatic Pressure Distribution in the Periodontal Ligament and the Risk of Root Resorption—A Finite Element Method (FEM) Study on the Nonlinear Innovative Model. Materials. 2024; 17(7):1661.

mój udział polegał na : przygotowaniu technicznym modelu do badań.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

GREG-DENT ORTHODONTICS SP. Z O.O.
ul. Prof. Tadeusza Kotarbińskiego 15, 91-163 Łódź
NIP: 9472008901, REGON: 523277314000
KRS: 0000993602
tel: 606 938 939, email: kontakt@greg-dent.pl
www.greg-dent.pl
GREG-DENT

OŚWIADCZENIE

Ja dr.n.med. Ewa Szeląg oświadczam, że w publikacjach:

Kotuła J, Kuc A, Szeląg E, Babczyńska A, Lis J, Matys J, Kawala B, Sarul M. Comparison of Diagnostic Validity of Cephalometric Analyses of the ANB Angle and Tau Angle for Assessment of the Sagittal Relationship of Jaw and Mandible. Journal of Clinical Medicine. 2023; 12(19):6333.

Kuc AE, Kotuła J, Nawrocki J, Szeląg E, Kawala B, Lis J, Sarul M. Morphological Evaluation of the Incisive Canal in the Aspect of the Diagnosis and Planning of Orthodontic Treatment—CBCT Study. Applied Sciences. 2023; 13(21):12010

mój udział polegał na : projektowaniu badań, pomocy w rekrutacji uczestników badań, analizie i interpretacji wyników.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

Ewa Szeląg

OŚWIADCZENIE

Ja lek.dent. Maciej Warnecki oświadczam, że w publikacji:

Kuc AE, Kotuła J, Nahajowski M, Warnecki M, Lis J, Amm E, Kawala B, Sarul M. Methods of Anterior Torque Control during Retraction: A Systematic Review. Diagnostics. 2022; 12(7):1611

mój udział polegał na : analizie i interpretacji wyników, przygotowaniu tabel i rycin.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

Maciej Warnecki

OŚWIADCZENIE

Ja Prof.dr.hab.n.med Beata Kawala oświadczam, że w publikacjach:

Kotuła J, Kuc AE, Lis J, Kawala B, Sarul M. New Sagittal and Vertical Cephalometric Analysis Methods: A Systematic Review. Diagnostics. 2022; 12(7):1723.

Kotuła J, Kuc A, Szeląg E, Babczyńska A, Lis J, Matys J, Kawala B, Sarul M. Comparison of Diagnostic Validity of Cephalometric Analyses of the ANB Angle and Tau Angle for Assessment of the Sagittal Relationship of Jaw and Mandible. Journal of Clinical Medicine. 2023; 12(19):6333.

Kuc AE, Kotuła J, Nahajowski M, Warnecki M, Lis J, Amm E, Kawala B, Sarul M. Methods of Anterior Torque Control during Retraction: A Systematic Review. Diagnostics. 2022; 12(7):1611

Kuc AE, Kotuła J, Nawrocki J, Kulgawczyk M, Kawala B, Lis J, Sarul M. Bone Remodeling of Maxilla after Retraction of Incisors during Orthodontic Treatment with Extraction of Premolars Based on CBCT Study: A Systematic Review. Journal of Clinical Medicine. 2024; 13(5):1503. https://doi.org/10.3390/jcm13051503

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Kuc AE, Kotuła J, Nawrocki J, Babczyńska A, Lis J, Kawala B, Sarul M. The Assessment of the Rank of Torque Control during Incisor Retraction and Its Impact on the Resorption of Maxillary Central Incisor Roots According to Incisive Canal Anatomy—Systematic Review. Journal of Clinical Medicine. 2023; 12(8):2774.

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mój udział polegał na : projektowaniu badań, przygotowaniu i korekcie manuskryptów oraz pozyskaniu finansowania badań.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

OŚWIADCZENIE

Ja lek.dent. Jakub Nawrocki oświadczam, że w publikacjach:

Kuc AE, Kotuła J, Nawrocki J, Kulgawczyk M, Kawala B, Lis J, Sarul M. Bone Remodeling of Maxilla after Retraction of Incisors during Orthodontic Treatment with Extraction of Premolars Based on CBCT Study: A Systematic Review. Journal of Clinical Medicine. 2024; 13(5):1503. https://doi.org/10.3390/jcm13051503

Kuc AE, Kotuła J, Nawrocki J, Babczyńska A, Lis J, Kawala B, Sarul M. The Assessment of the Rank of Torque Control during Incisor Retraction and Its Impact on the Resorption of Maxillary Central Incisor Roots According to Incisive Canal Anatomy—Systematic Review. Journal of Clinical Medicine. 2023; 12(8):2774.

Kuc AE, Kotuła J, Nawrocki J, Szeląg E, Kawala B, Lis J, Sarul M. Morphological Evaluation of the Incisive Canal in the Aspect of the Diagnosis and Planning of Orthodontic Treatment—CBCT Study. Applied Sciences. 2023; 13(21):12010

mój udział polegał na : analizie i interpretacji wyników, przygotowaniu rycin i tabel.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

Jakub Nawrocki

OŚWIADCZENIE

Ja Prof.dr.hab.n.med. Joanna Lis oświadczam, że w publikacjach:

Kotuła J, Kuc AE, Lis J, Kawala B, Sarul M. New Sagittal and Vertical Cephalometric Analysis Methods: A Systematic Review. Diagnostics. 2022; 12(7):1723.

Kotuła J, Kuc A, Szeląg E, Babczyńska A, Lis J, Matys J, Kawala B, Sarul M. Comparison of Diagnostic Validity of Cephalometric Analyses of the ANB Angle and Tau Angle for Assessment of the Sagittal Relationship of Jaw and Mandible. Journal of Clinical Medicine. 2023; 12(19):6333.

Kuc AE, Kotuła J, Nahajowski M, Warnecki M, Lis J, Amm E, Kawala B, Sarul M. Methods of Anterior Torque Control during Retraction: A Systematic Review. Diagnostics. 2022; 12(7):1611

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Kuc AE, Sybilski K, Kotuła J, Piątkowski G, Kawala B, Lis J, Saternus S, Sarul M. The Hydrostatic Pressure Distribution in the Periodontal Ligament and the Risk of Root Resorption—A Finite Element Method (FEM) Study on the Nonlinear Innovative Model. Materials. 2024; 17(7):1661.

Kuc AE, Kotuła J, Nawrocki J, Babczyńska A, Lis J, Kawala B, Sarul M. The Assessment of the Rank of Torque Control during Incisor Retraction and Its Impact on the Resorption of Maxillary Central Incisor Roots According to Incisive Canal Anatomy—Systematic Review. Journal of Clinical Medicine. 2023; 12(8):2774.

Kuc AE, Kotuła J, Nawrocki J, Szeląg E, Kawala B, Lis J, Sarul M. Morphological Evaluation of the Incisive Canal in the Aspect of the Diagnosis and Planning of Orthodontic Treatment—CBCT Study. Applied Sciences. 2023; 13(21):12010

mój udział polegał na : analizie i interpretacji wyników, przygotowaniu i korekcie manuskryptów.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

OŚWIADCZENIE

Ja Prof.dr.hab.n.med. Michał Sarul oświadczam, że w publikacjach:

Kotuła J, Kuc AE, Lis J, Kawala B, Sarul M. New Sagittal and Vertical Cephalometric Analysis Methods: A Systematic Review. Diagnostics. 2022; 12(7):1723.

Kotuła J, Kuc A, Szeląg E, Babczyńska A, Lis J, Matys J, Kawala B, Sarul M. Comparison of Diagnostic Validity of Cephalometric Analyses of the ANB Angle and Tau Angle for Assessment of the Sagittal Relationship of Jaw and Mandible. Journal of Clinical Medicine. 2023; 12(19):6333.

Kuc AE, Kotuła J, Nahajowski M, Warnecki M, Lis J, Amm E, Kawala B, Sarul M. Methods of Anterior Torque Control during Retraction: A Systematic Review. Diagnostics. 2022; 12(7):1611

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Kuc AE, Sybilski K, Kotuła J, Piątkowski G, Kawala B, Lis J, Saternus S, Sarul M. The Hydrostatic Pressure Distribution in the Periodontal Ligament and the Risk of Root Resorption—A Finite Element Method (FEM) Study on the Nonlinear Innovative Model. Materials. 2024; 17(7):1661.

Kuc AE, Kotuła J, Nawrocki J, Babczyńska A, Lis J, Kawala B, Sarul M. The Assessment of the Rank of Torque Control during Incisor Retraction and Its Impact on the Resorption of Maxillary Central Incisor Roots According to Incisive Canal Anatomy—Systematic Review. Journal of Clinical Medicine. 2023; 12(8):2774.

Kuc AE, Kotuła J, Nawrocki J, Szeląg E, Kawala B, Lis J, Sarul M. Morphological Evaluation of the Incisive Canal in the Aspect of the Diagnosis and Planning of Orthodontic Treatment—CBCT Study. Applied Sciences. 2023; 13(21):12010

mój udział polegał na : formułowaniu problemów i hipotez badawczych, projektowaniu badań, pomocy w rekrutacji uczestników badań, analizie i interpretacji wyników, przygotowaniu i korekcie manuskryptów oraz pozyskaniu finansowania.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

OŚWIADCZENIE

Ja mgr inż. Szymon Saternus oświadczam, że w publikacji:

Kuc AE, Sybilski K, Kotuła J, Piątkowski G, Kawala B, Lis J, Saternus S, Sarul M. The Hydrostatic Pressure Distribution in the Periodontal Ligament and the Risk of Root Resorption—A Finite Element Method (FEM) Study on the Nonlinear Innovative Model. Materials. 2024; 17(7):1661.

mój udział polegał na: projektowaniu modelu FEM, przygotowaniu tabel i rycin.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

Saternus Szymon

OŚWIADCZENIE

Ja lek.dent. Maria Kulgawczyk oświadczam, że w publikacji:

Kuc AE, Kotuła J, Nawrocki J, Kulgawczyk M, Kawala B, Lis J, Sarul M. Bone Remodeling of Maxilla after Retraction of Incisors during Orthodontic Treatment with Extraction of Premolars Based on CBCT Study: A Systematic Review. Journal of Clinical Medicine. 2024; 13(5):1503. https://doi.org/10.3390/jcm13051503

mój udział polegał na : przygotowaniu tabel i analizie wyników.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

Maria Kulgawczyk

OŚWIADCZENIE

Ja dr n. med. Jacek Matys oświadczam, że w publikacji:

Kotuła J, Kuc A, Szeląg E, Babczyńska A, Lis J, Matys J, Kawala B, Sarul M. Comparison of Diagnostic Validity of Cephalometric Analyses of the ANB Angle and Tau Angle for Assessment of the Sagittal Relationship of Jaw and Mandible. Journal of Clinical Medicine. 2023; 12(19):6333.

mój udział polegał na : pomocy w rekrutacji uczestników badań, analizie i interpretacji wyników.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

Jacek Matys

OŚWIADCZENIE

Ja dr.n.med. Marek Nahajowski oświadczam, że w publikacji:

Kuc AE, Kotuła J, Nahajowski M, Warnecki M, Lis J, Amm E, Kawala B, Sarul M. Methods of Anterior Torque Control during Retraction: A Systematic Review. Diagnostics. 2022; 12(7):1611

mój udział polegał na : przygotowaniu tabel, analizie i interpretacji wyników, przygotowaniu i korekcie manuskryptów.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

Marek Nahajowski

OŚWIADCZENIE

Ja Elie Amm oświadczam, że w publikacji:

Kuc AE, Kotuła J, Nahajowski M, Warnecki M, Lis J, Amm E, Kawala B, Sarul M. Methods of Anterior Torque Control during Retraction: A Systematic Review. Diagnostics. 2022; 12(7):1611

mój udział polegał na : przygotowaniu i korekcie manuskryptów.

Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

Ja lek.dent. Alicja Babczyńska oświadczam, że w publikacjach:

Kotuła J, Kuc A, Szeląg E, Babczyńska A, Lis J, Matys J, Kawala B, Sarul M. Comparison of Diagnostic Validity of Cephalometric Analyses of the ANB Angle and Tau Angle for Assessment of the Sagittal Relationship of Jaw and Mandible. Journal of Clinical Medicine. 2023; 12(19):6333.
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mój udział polegał na : pomocy w rekrutacji uczestników badań, analizie i interpretacji wyników.
Wyrażam zgodę na włączenie przez lek. dent. Annę Ewę Kuc w/w publikacji w postępowaniu o nadanie stopnia doktora w dziedzinie nauk medycznych i nauk o zdrowiu w dyscyplinie nauki medyczne.

Alicja Babczyńska