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IZVORNI ZNANSTVENI RAD

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Measurement of the Dentin Wall Thickness of the Maxillary Central Incisor in Relation to the Stage of Root Development: A Pilot Study

Mjerenje debljine dentinskoga zida maksilarnog središnjeg sjekutića u odnosu na stadij razvoja korijena: pilot-studija

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Abstract
Objective: The aim of this study was to determine the average dentin wall thickness (DWT) of the maxillary central incisor (MCI) required for performing finite element analysis (FEA) models of root development. **Material and methods:** A total of 137 intraoral periapical radiographs of MCI in children aged 7 to 11 years were examined and then classified into 5 groups according to root development stages, which included 1/2 of root development (S1), 3/4 of root development (S2), more than 3/4 of root development (S3), complete development with wide-open apex (S4) and complete development with closed apex (S5). DWT was measured at three reference (horizontal) lines: at a distance of 1 mm from the apex (M), 4 mm from the apex (L) and at the cervical line (K). The distal dentin wall thickness (M1, L1, and K1), the pulp thickness (M2, L2, and K2), the mesial dentin wall thickness (M3, L3, and K3), and the apex thickness (N) were measured using the diagnostic software Soredex Scanora 5.1.2.4. Statistical analysis compared the values of the parameters K, L, and M between developmental stages (multivariate ANOVA) and the linear correlations between the parameters (Pearson's correlation analysis). All analyses were performed at significance level $\alpha = 0.05$. **Results:** There were statistically significant differences between the developmental stages for parameters L and M, while no significant differences were found for parameter K. Most of the correlations between the parameters were statistically significant, with the values of the Pearson correlation coefficient $R > 0.6$ considered practically significant. All parameters on the same reference line for distal and mesial dentin wall thickness and for pulp thickness correlated well with each other ($R = 0.46 – 0.68$), but there was no statistically significant correlation with total root thickness on the same reference line (parameters K, L, or M), except for parameter K3 ($R = 0.42$). **Conclusion:** Despite the limitations of this study, the mean values of the selected parameters for the 5 groups of developmental stages of the maxillary central incisor could be used to model dentin wall thickness using finite element analysis.

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Introduction

The treatment of dental trauma is not a common situation in everyday dental practice (1-4). Many clinical studies have shown that over 50% of immature teeth treated endodontically are lost in the first ten years (5-7). For these reasons, the analysis of masticatory function, especially the biomechanical response after dental trauma, is of great importance for un-

Uvod

Liječenje dentalne traume nije često u svakodnevnom stomatološkom radu (1 – 4). U mnogim kliničkim studijama autori su istaknuli da je više od 50 % nezrelih endodontski liječenih mladih trajnih zuba izgubljeno u prvih deset godina (5 – 7). Zbog toga je analiza žvačne funkcije, posebice biomehaničkog odgovora poslije dentalne traume, veoma važna derstanding the problem of treatment failure and for finding more suitable reconstructive materials and methods (8).

The stress distribution within the tooth and the surrounding tissue is very complex due to the inhomogeneous importance of the structures that compose them, the irregularities of the contours and their external shape, and the complex internal morphology (9). The finite element method (FEM) is a new and important research tool for biomechanical analysis (10). Using mathematical equations, computer analysis converts a physical problem into a virtual model represented by finite element software (11). The method represents the simulated mechanical behavior of teeth under occlusal loading (12). The necessary step for implementation is the construction of a finite element model, followed by the specification of appropriate material properties, loads, and boundary conditions (8). Finite element analysis (FEA) effectively simulates a real clinical scenario and solves complex problems by predicting long-term failures (11). The results include information about the stress distribution in each component as opposed to single values obtained in *in vitro* research (12). In addition, FEM reduces research time and allows ethical and methodological constraints to be overcome, which is why it is often used for complex studies in dentistry (10, 12).

Traumatic injuries to permanent teeth are very common in school-age children, especially between the ages of eight and ten years (13), when root development is not yet complete. The maxillary central incisor (MCI) is the tooth most frequently affected by trauma, which usually results in a crown fracture (14-16). A fracture may be uncomplicated or complicated, i.e., with or without exposure of the pulp. The primary goal of treatment is to preserve the pulp vitality and restore aesthetics and function (17). Endodontic treatment is required when all efforts to preserve vitality are unsuccessful or when the patient has already presented with such a condition. Due to the immaturity of the teeth, it is considered one of the most complex challenges for clinicians (15, 18).

Many studies have evaluated the stress distribution in endodontically weakened root canals using FEM (19-21), but there have not yet been any data in the literature on the biomechanical response of MCI depending on the stage of root development. The average length values in the general population for intact MCI with completed root development were taken from the literature (22), but there have been no data on the average dentin thickness. The aim of this study was to determine the average dentin wall thickness (DWT) of MCI required for the construction of finite element analysis models of root development.

Material and methods

This study is part of a dissertation study approved by the Ethics Committee, School of Dentistry, University of Zagreb, Croatia (Approval number: 05- PA -27-5/2018.). For the use of radiographs, it was sufficient for the child's parents or guardians to sign an informed consent form before each treatment at the Department of Pediatric and Preventive Dentistry, University Hospital Centre Zagreb, which also included consent to use the radiographs for research purposes. A total of 137

za razumijevanje problema povezanog s neuspjehom liječenja i za pronalaženje prikladnijih rekonstrukcijskih materijala i metoda (8).

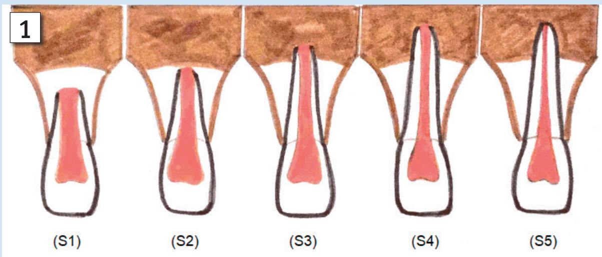
Raspodjela naprezanja unutar zuba i okolnoga tkiva vrlo je složena zbog nehomogene važnosti struktura koje ih čine, nepravilnosti kontura i vanjskog oblika te složene unutarnje morfologije (9). Metoda konačnih elemenata (MKE) novi je i važan istraživački alat za biomehaničku analizu (10). Koristeći se matematičkim jednadžbama, računalna analiza pretvara fizički problem u virtualni model zahvaljujući softveru konačnih elemenata (11). Metoda zapravo pokazuje simulirano mehaničko ponašanje zuba pod okluzijskim opterećenjem (12). Nužan korak za implementaciju jest izrada modela konačnih elemenata, nakon čega slijedi specifikacija odgovarajućih svojstava materijala, opterećenja i rubnih uvjeta (8). Analiza konačnih elemenata učinkovito simulira stvarni klinički scenarij i rješava složene probleme predviđanjem dugoročnih neuspjeha (11). Rezultati uključuju podatke o raspodjeli stresa u svakoj komponenti, za razliku od pojedinačnih vrijednosti dobivenih istraživanjem *in vitro* (12). Uz to, MKE skraćuje vrijeme istraživanja i omogućuje prevladavanje etičkih i metodoloških ograničenja zbog čega se često primjenjuje za složena istraživanja u stomatologiji (10, 12).

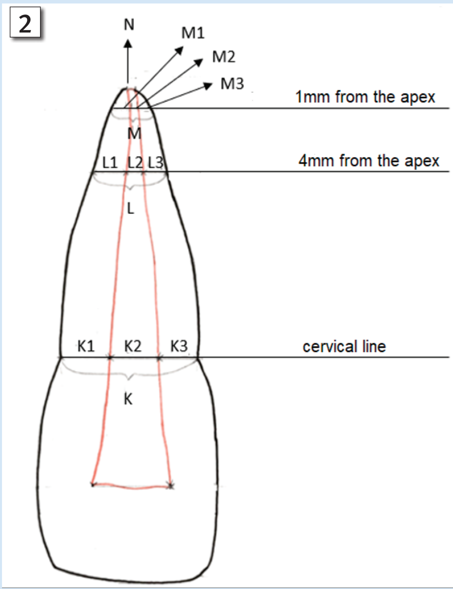
Traumatske ozljede trajnih zuba vrlo su česte kod djece školske dobi, osobito između osme i desete godine (13) kada razvoj korijena još nije završen. Maksilarni središnji sjekutić (MSS) zub je koji je najčešće zahvaćen traumom, a to obično rezultira prijelomom krune (14 – 16). Prijelom može biti nekompliciran ili kompliciran, tj. s izloženom ili neizloženom pulpom. Primarna svrha liječenja je očuvati vitalitet pulpe te vratiti estetiku i funkciju (17). Endodontsko liječenje potrebno je kada su svi napori da se očuva vitalitet neuspješni ili pacijent već ima takvo stanje. Zbog nezrelosti zuba smatra se jednim od najsloženijih izazova za kliničare (15, 18).

Autori mnogih studija procjenjivali su preraspodjelu stresa u endodontski oslabljenim korijenskim kanalima s pomoću metode konačnih elemenata (19 – 21), ali u literaturi se ne nalaze podatci o biomehaničkom odgovoru MSS-a ovisno o stupnju razvoja korijena. Vrijednosti prosječne dužine za intaktni MSS sa završenim razvojem korijena u općoj populaciji preuzete su iz literature (22), a vrijednosti o prosječnoj debljini dentina nisu bile poznate. Cilj ovog istraživanja bio je odrediti prosječne vrijednosti debljine dentinskoga zida (DDZ) za MSS koje su potrebne za konstruiranje modela razvoja korijena metodom konačnih elemenata.

Materijali i metode

Ovaj je rad dio disertacijske studije koju je odobrilo Etičko povjerenstvo Stomatološkog fakulteta Sveučilišta u Zagrebu (broj odobrenja: 05-PA -27-5/2018.). Za korištenje rendgenskih snimki bilo je dovoljno da roditelji ili skrbnici djeteta potpišu uobičajeni informirani pristanak prije svakoga dentalnog zahvata u Zavodu za dječju i preventivnu stomatologiju KBC-a Zagreb, u njegovu sklopu bio je i pristanak za korištenje rendgenskih snimaka u istraživačke svrhe. Pregledano





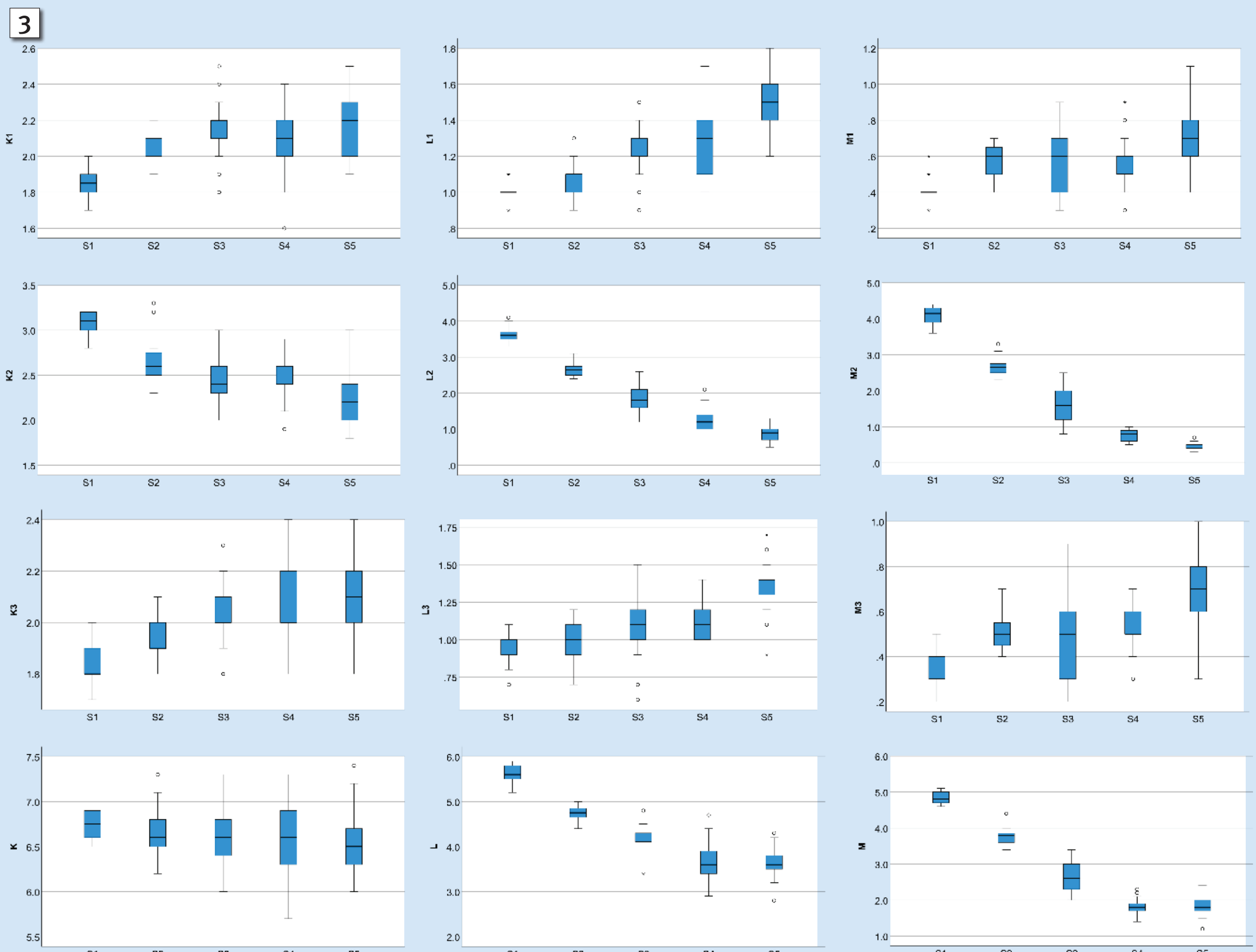


Figure 1 Root development stages (S1) 1/2 of the root development, (S2) 3/4 of the root development, (S3) more than 3/4 of the root development, (S4) complete development with wide-open apex, (S5) and complete development with closed apex.

Slika 1. Stadiji razvoja korijena (S1) 1/2 razvoja korijena, (S2) 3/4 razvoja korijena, (S3) više od 3/4 razvoja korijena, (S4) potpuno razvijen korijen s otvorenim apeksom (S5) i potpuno razvijeni korijen sa zatvorenim apeksom

Figure 2 The dentin wall thickness at three reference (horizontal) lines: at a distance of 1mm from the apex (M), 4mm from the apex (L), and at the cervical line (K). The distal dentin wall thickness (M1, L1, and K1), the pulp thickness (M2, L2, and K2), the mesial dentin wall thickness (M3, L3, and K3), and the apex thickness (N).

Slika 2. Debljina dentinskoga zida na trima referentnim (horizontalnim) linijama: na udaljenosti od 1 mm od apeksa (M), 4 mm od apeksa (L) i na razini cervikalne linije (K); debljina distalnoga zida dentina (M1, L1 i K1), debljina pulpe (M2, L2 i K2), debljina mezijalnog zida dentina (M3, L3 i K3) i debljina apikalnog otvora (N)

Figure 3 The distribution of root dimensions divided into 5 stages of root development. The boxplots show medians (bold black lines) and the boxes represent the 25% and 75% quartiles. The 1.5 × interquartile range is represented by whiskers. Outliers are presented by circles.

Slika 3. Distribucija dimenzija korijena podijeljena u 5 stadija razvoja korijena; okvirni dijagrami prikazuju medijane (podebljane crne linije), a okviri predstavljaju kvartile od 25 % i 75 %; 1,5 × interkvartilni raspon označen je donjim i gornjim horizontalnim linijama; outlieri su označeni kružićima intraoral periapical radiographs of MCI in children aged 7 to 11 years indicated for diagnostic purposes were examined and then classified into 5 groups according to the stages of root development, which included 1/2 of root development (S1), 3/4 of root development (S2), more than 3/4 of root development (S3), complete development with wide open apex (S4), and complete development with closed apex (S5) (Figure 1). The dentin wall thickness was measured at three reference (horizontal) lines: at a distance of 1 mm from the apex (M), 4 mm from the apex (L) and at the cervical line (K). The distal dentin wall thickness (M1, L1 and K1), the pulp thickness (M2, L2 and K2), the mesial dentin wall thickness (M3, L3 and K3) and the apex thickness (N) were measured using the diagnostic software Soredex Scanora 5.1.2.4 (Figure 2). All measurements were performed by a single person.

The average length values in the general population for intact MCI with completed root development were taken from the literature: 23.5 mm for tooth length, 10.5 mm for crown length and 13.0 mm for root length (18). The mean root lengths for the other stages calculated from the mean lengths for MCI with complete root development were as follows: 6.5 mm for S1, 9.7 mm for S2, between 9.7 mm and 13.00 mm for S3, and 13.0 mm for S4 and S5. All stages except S3 were classified according to the proposed root-to-crown length ratio (Table 1), whereas for stage S3, the range between stages S2 and S4 was considered, i.e., root lengths from 10.0 mm to 12.5 mm and their root-to-crown length ratio to avoid errors in the final range values, which were then closer to stage 2 or 4. Stages S4 and S5 were differentiated according to apical closure status, with N above 0.45 mm considered S4 unless when the expected age of the child was a more decisive factor (> 10 years). All measurements were performed by a single person.

The normality of data distribution was evaluated using the Kolmogorov-Smirnov test and normal Q-Q diagrams. Statistical analysis compared the values of parameters K, L, and M between developmental stages (multivariate ANOVA) and linear correlations between parameters (Pearson's correlation analysis). All analyses were performed at a significance level of α = 0.05.

Results

The values of the individual numerical parameters, divided into 5 groups (stages of development), generally did not deviate significantly from the normal distribution (Figure 3). For parameters L and M, there were statistically significant

je ukupno 137 intraoralnih periapikalnih rendgenskih slika MSS-a djece u dobi od 7 do 11 godina indiciranih u dijagnostičke svrhe koje su zatim bile podijeljene u 5 skupina prema stadijima razvoja korijena, a uključivale su stadije u kojima je razvijena jedna polovina korijena zuba (S1), tri četvrtine korijena zuba (S2), više od tri četvrtine korijena zuba (S3), potpuno razvijeni korijen s otvorenim apeksom (S4) te potpuno razvijeni korijen sa zatvorenim apeksom (S5) (slika 1.). DDZ je mjeren na trima referentnim (horizontalnim) linijama na 1 mm od apeksa (M), 4 mm od apeksa (L) te na razini cervikalne linije (K). Izmjerena je debljina distalnoga zida dentina (M1, L1 i K1), debljina pulpe (M2, L2 i K2), debljina mezijalnog zida dentina (M3, L3 i K3) i debljina apikalnog otvora (N) u dijagnostičkom softveru Soredex Scanora 5.1.2.4 (slika 2.). Sva mjerenja obavila je jedna osoba.

Prosječne vrijednosti dužine za intaktni MSS sa završenim razvojem korijena u općoj populaciji preuzete su iz literature (22): 23,5 mm za dužinu cijelog zuba, 10,5 mm za dužinu krune zuba i 13,0 mm za dužinu korijena. Prema tome srednje vrijednosti dužine korijena za ostale stadije, izračunate prema srednjim vrijednostima dužine za intaktni MSS, iznosile su 6,5 mm za S1, 9,7 mm za S2, 9,7 mm – 13,0 mm za S3 te 13,0 mm za S4 i S5. Svi stadiji, osim S3, klasificirani su prema predloženom omjeru dužine korijena i krune (tablica 1.), a za stadij S3 razmatran je raspon između stadija S2 i S4, odnosno dužine korijena od 10,0 mm do 12,5 mm i odgovarajući omjeri dužine korijena i krune kako bi se izbjegle pogreške u graničnim vrijednostima raspona koje su tada bile bliže stadiju 2 ili 4. Stadiji S4 i S5 diferencirani su prema statusu apikalnog otvora, pri čemu se N > 0,45 mm smatrao S4, osim ako je očekivana dob djeteta bila odlučujući čimbenik (> 10 godina).

Normalnost distribucije podataka procijenjena je Kolmogorov-Smirnovljevim testom i normalnim Q-Q dijagramima. U statističkoj analizi uspoređene su vrijednosti parametara K, L i M između pojedinih razvojnih stadija (multivarijatna ANOVA) te linearne korelacije između parametara (Pearsonova korelacijska analiza). Sve analize provedene su na razini značajnosti α = 0,05.

Rezultati

Vrijednosti pojedinih numeričkih parametara, podijeljenih u 5 skupina (stadija razvoja), uglavnom nisu znatno odstupale od normalne distribucije (slika 3.). Parametri L i M statistički su se značajno razlikovali između razvojnih stadija,

Table 1 The root-to-crown length ratio of mean values for MCI (18) depending on the root development stage.
Tablica 1. Omjer dužine korijena i krune prema srednjim vrijednostima dužine za MSS (18) u ovisnosti o stadiju razvoja korijena

Stage • Stadij	Mean crown length • Srednja vrijednost dužine krune (mm)	Mean root length • Srednja vrijednost dužine korijena (mm)	Root-to-crown ratio • Omjer korijena i krune
S1	10.5	6.5	1:1.62
S2		9.7	1:1.08
S3		10.0 – 12.5	1:1.05 – 1:0.84
S4		13.0	1:0.81
S5		13.0	1:0.81

Table 2 Results of multivariate ANOVA for comparisons of root dimensions among developmental stages.
Tablica 2. Rezultati multivarijatne ANOVA-e kod usporedbe dimenzija korijena između razvojnih faza

Dentinal wall thickness (DTW) • Debljina dentinskoga zida (DDZ)		Type III Sum of Squares • Zbroj kvadrata tipa III	df • Stupnjevi slobode	Mean Square • Srednji kvadrat	F	Sig. • p-vrijednost
	K1	1.031[a]	4	.258	10.464	.000
	K2	5.369[b]	4	1.342	18.886	.000
	K3	.654[c]	4	.163	7.877	.000
	K	.345[d]	4	.086	.680	.608
	L1	2.135[e]	4	.534	25.086	.000
	L2	71.685[f]	4	17.921	201.326	.000
	L3	1.787[g]	4	.447	16.625	.000
	L	36.305[h]	4	9.076	79.893	.000
	M1	.865[i]	4	.216	8.848	.000
	M2	122.365[j]	4	30.591	317.497	.000
	M3	.855[k]	4	.214	10.910	.000
	M	93.510[l]	4	23.378	299.004	.000
	N	140.106[m]	4	35.027	327.628	.000

Table 3 The mean values of dentin wall thickness for the 5 groups of developmental stages of the maxillary central incisor.
Tablica 3. Srednje vrijednosti debljine stijenke dentina za 5 skupina razvojnih stadija kod gornjega središnjeg sjekutića

	K1	K2	K3	K	L1	L2	L3	L	M1	M2	M3	M	N
S1	1.840± 0.069	3.080± 0.100	1.820± 0.066	6.740± 0.102	1.000± 0.048	3.660± 0.169	0.950± 0.091	5.610± 0.160	0.420± 0.056	4.070± 0.191	0.340± 0.069	4.820± 0.125	4.240± 0.211
S2	2.033± 0.049	2.683± 0.191	1.942± 0.064	6.658± 0.192	1.075± 0.072	2.650± 0.134	1.008± 0.091	4.733± 0.109	0.583± 0.059	2.675± 0.182	0.508± 0.057	3.767± 0.175	2.817± 0.236
S3	2.148± 0.072	2.471± 0.118	2.019± 0.057	6.638± 0.162	1.210± 0.061	1.876± 0.187	1.048± 0.094	4.133± 0.144	0.581± 0.084	1.586± 0.242	0.481± 0.084	2.648± 0.175	1.490± 0.244
S4	2.086± 0.088	2.452± 0.115	2.081± 0.084	6.619± 0.206	1.267± 0.086	1.271± 0.152	1.138± 0.067	3.676± 0.210	0.543± 0.071	0.767± 0.086	0.500± 0.056	1.810± 0.111	0.683± 0.078
S5	2.200± 0.069	2.252± 0.124	2.084± 0.064	6.536± 0.141	1.460± 0.062	0.848± 0.078	1.344± 0.065	3.652± 0.133	0.736± 0.072	0.436± 0.039	0.660± 0.063	1.832± 0.098	0.400± 0.047

differences between the developmental stages, while no significant differences were found for parameter K (Table 2). Most of the correlations between the parameters were statistically significant, with values of the Pearson correlation coefficient R > 0.6 considered practically significant. All parameters for pulp thickness correlated well with each other (R = 0.61 – 0.99) and with root thickness at a distance of 4 mm and 1 mm from the apex (R = 0.60 – 0.95), but did not correlate with root thickness at the cervical line, except for parameter K2 (R = 0.64). All parameters on the same reference line for distal and mesial dentin wall thickness and for pulp thickness correlated well with each other (R = 0.46 – 0.68), but there was no statistically significant correlation with total root thickness on the same reference line (parameters K, L, or M), except for parameter K3 (R = 0.42). Root thickness at a distance of 4 mm from the apex correlated well with pulp thickness (R = 0.90), but there was no statistically significant correlation with distal and mesial dentin wall thickness. The parameters K and K1 showed significantly lower correlations than all other parameters, while the parameter K2 correlated with all measured parameters (R = (-0.26) – 0.70).

The mean values of dentin wall thickness for the 5 groups of developmental stages of the maxillary central incisor are shown in Table 3.

a za parametar K nisu opažene značajne razlike (tablica 2.). Većina korelacija između parametara bila je statistički značajna, a vrijednosti Pearsonova koeficijenta korelacije R > 0,6 smatrane su praktički značajnima. Svi parametri za debljinu pulpe uzajamno su dobro korelirali (R = 0,61 – 0,99) kao i s debljinom korijena na udaljenosti 4 mm i 1 mm od apeksa (R = 0,60 – 0,95), ali nisu korelirali s debljinom korijena na cervikalnoj liniji, osim parametra K2 (R = 0,64). Svi parametri za debljinu dentinske stijenke prema distalno i mezijalno te za debljinu kanala uzajamno su dobro korelirali na svojoj referentnoj liniji (R = 0,46 – 0,68), a nisu statistički značajno korelirali s ukupnom debljinom na svojoj referentnoj liniji (parametri K, L ili M), osim parametra K3 (R = 0,42). Debljina korijena 4 mm od apeksa dobro je korelirala s debljinom pulpe (R = 0,90), ali nije bilo statistički značajne korelacije s debljinom distalnoga i mezijalnoga dentinskoga zida. Parametri K i K1 pokazali su značajno manje korelacije od svih ostalih parametara, a parametar K2 korelirao je sa svim mjerenim parametrima (R = (-0,26) – 0,70).

Srednje vrijednosti debljine dentinskoga zida za 5 skupina rasta i razvoja korijena za maksilarni središnji sjekutić prikazane su u tablici 3.

Discussion

Numerous studies have evaluated stress distribution in endodontically treated ("endodontically weakened") maxillary incisors, usually after postendodontic restoration using FEM, but only a few of them evaluated immature incisors (23-28). In these studies, different methods were used to model an immature incisor for FEA, defining immaturity in general or a specific stage, but there was no protocol for creating FEA models for all stages of root development. The main reason for this is that there are no data in the literature on average dentin thickness depending on the root development stage.

CBCT is commonly used for dental measurements because it provides high accuracy and detection of surrounding tissue (29, 30). Although the absorbed dose of X-rays has been greatly reduced compared to CT, the dose is still higher than panoramic radiography (PAN) (29, 31). There is no justification for its use unless it is not primarily indicated for other diagnostic or therapeutic reasons, especially in children (32-34). Mazzotta et al. (2013) reported that it is possible to create a 3D parametric model with a clinically valid degree of accuracy starting from 2D information (35). They measured tooth height, crown and root height, CEJ width, width of the widest and highest part of the crown, and width of the root at half root length for monoradicular teeth. In our study, similar measurements were made for the root, and additional measurements were made 4 mm and 1 mm from the apex. Accordingly, data from 2D images were sufficiently accurate to obtain mesial/distal measurements, but the disadvantage was that it was impossible to obtain buccal/lingual measurements from a panoramic radiograph. Nevertheless, after reviewing the literature, we decided to use the CBCT of the maxillary central incisor with completed root development for a personalized base model so that the initial buccal-oral dimension would be considered for modelling the other models of root development. Also, the pulp canal of the central incisor is almost equidistant to all edges of the root (36), the mesio-distal and buccal-oral dimensions are almost the same.

Back in 2007, Talati et al (23) designed two models of MCI, a mature and an open-apex model. The geometry of the mature tooth was taken from the literature (37), with simulation of endodontic canal instrumentation in taper form (master apical file #40, coronal opening diameter 1.60 mm) and gutta-percha filling. Buccolingual and mesiodistal measurements for an immature tooth were taken on an extracted incisor with an open apex, additionally simulating an MTA plug and endodontic filling with gutta-percha. Although the dimensions of the mature incisor for the basic FEA model are now much more accurate, mainly due to the method of tooth isolation from the CBCT, the study still confirmed that the pattern of stress distribution is different in mature and immature teeth, paving the way for further research in this area. Since then, there have been several studies using different methods to model a weakened or immature incisor for FEA. Usually, a basic 3D geometric model was reconstructed from the CBCT of an intact or extracted incisor, and then additional models were created in the programme

Rasprava

Autori mnogih studija procjenjivali su preraspodjelu stresa u endodontski liječenim („endodontski oslabljenim") maksilarnim sjekutićima, obično poslije postendodontske restauracije korištenjem MKE-a, ali samo je nekoliko njih procjenjivalo mlade trajne sjekutiće (23 – 28). U tim istraživanjima korištene su različite metode za konstruiranje nezrelog sjekutića definirajući općenito nezrelost korijena ili pojedini stadij, ali nisu sadržavale protokol za izradu modela za sve stadije razvoja korijena. Glavni razlog jest to što u literaturi nema podataka o prosječnoj debljini dentina u odnosu prema stadiju razvoja korijena.

Za dentalna mjerenja obično se upotrebljava CBCT jer omogućuje visoku točnost i detekciju okolnoga tkiva (29, 30). Iako je apsorbirana doza rendgenskih zraka znatno smanjena u usporedbi s CT-om, još je uvijek viša nego pri snimanju panoramske snimke (PAN) (29, 31). Ako CBCT nije primarno indiciran iz dijagnostičkih ili terapijskih razloga, nema opravdanja za njegovu primjenu osobito kad je riječ o djeci (32 – 34). Mazzotta i suradnici (2013.) izvijestili su da se, počevši od 2D informacije, može izraditi 3D parametrijski model s klinički valjanim stupnjem točnosti (35). U svojoj studiji mjerili su visinu zuba, visinu krune i korijena, širinu caklinsko-cementnoga spojišta (CCS), širinu najširega i najvišega dijela krune zuba te širinu korijena na polovini dužine za monoradikularne zube. U našem istraživanju obavljena su slična mjerenja za širinu korijena uz dodatna dva na udaljenosti od 4 mm i 1 mm od apeksa. U skladu s tim podatci s dvodimenzionalne slike bili su dovoljno točni za dobivanje informacije o mezijalnoj i distalnoj debljini korijena, a podatci o bukalnoj i oralnoj debljini nedostajali su kod panoramske radiografije. Nakon pregleda literature odlučeno je da se u nastavku istraživanja upotrijebi jedan CBCT maksilarnoga središnjeg sjekutića sa završenim razvojem korijena za izolaciju personaliziranog osnovnog modela kako bi se početna bukalno-oralna dimenzija ipak uzela u obzir pri oblikovanju ostalih modela razvoja korijena. Iako je pulpni kanal MSS-a jednako udaljen od svih rubova korijena (36), mezio-distalna i bukalno-oralna dimenzija gotovo su jednake.

Još su 2007. godine Talati i suradnici (23) dizajnirali dva modela MSS-a – zreli sjekutić i sjekutić s otvorenim apeksom. Geometrija zrelog sjekutića preuzeta je iz literature (37) sa simulacijom instrumentacije endodontskog kanala u koničnom obliku (MAF #40, promjer apikalnog otvora 1,60 mm) i gutaperkinim punjenjem. Bukolingvalna i meziodistalna mjerenja za nezreli sjekutić obavljena su na izvađenom sjekutiću s otvorenim apeksom, dodatno simulirajući mineraltrioksid (MTA) apikalni stop i endodontsko punjenje kanala gutaperkom. Iako su dimenzije zrelog sjekutića za osnovni MKE model danas mnogo točnije uglavnom zahvaljujući metodi izolacije zuba s CBCT-a, studija je ipak potvrdila da je model raspodjele stresa različit kod zrelih i nezrelih zuba, pripremajući sadržaj za daljnja istraživanja u ovom području. Od tada su se u nekoliko studija primjenjivale različite metode za modeliranje oslabljenog ili nezrelog sjekutića za analizu konačnih elemenata. Osnovni 3D geometrijski model obično se rekonstruirao s CBCT-a intaktnoga ili izvaor directly on the extracted incisor according to the required tooth properties.

Khadar et al (24) used prepared extracted MCI to simulate immature incisors with thin dentin walls and open apex. After root instrumentation (master apical file set at # 80), the apex was enlarged to 1 mm with Peeso drills to define immaturity in general. Eram et al. (25) also prepared an extracted MCI before subjecting it to a CBCT examination to simulate an immature incisor according to Cvek's third stage (7). The root was shortened apically by 4 mm (tooth length was 21 mm and root length was 9 mm). After root instrumentation (master apical file # 80), the open apex was extended 1 mm beyond the apex to 1.7 mm with Peeso drills. The root-canal ratio was approximately 1:1 in the mesiodistal dimension at CEJ. These dimensions were higher to our third stage of root development: apex width 1.490±0.244 mm and root-canal ratio at the CEJ 1:1.19, except for the average root width (11.0 mm). In the study by Anthrayose et al (22) CBCT scans of permanent maxillary central incisors and available literature data were used to simulate an immature MCI model at Cvek stage 3 in the programme, with an apical opening of 1.67 mm and a root length approximately 3 mm less than that of the mature tooth, i.e. 10.5 mm, which is more in agreement with our measurements. This study had a similar protocol to ours, but described only one stage of root development and the proposed root dimensions. The study by Dezzen-Gomide et al. (27) presented three different stages of MCI root development: complete rhizogenesis, incomplete rhizogenesis in the apical third of the root, and incomplete rhizogenesis in the middle third of the root. The model of complete rhizogenesis was based on a CBCT of an extracted incisor. The two models of incomplete rhizogenesis were modified based on anatomical references from 6 CBCT studies of immature MCI (patients aged 7 to 12 years) at different stages of rhizogenesis, but without describing the values obtained. Dezzen-Gomide et al. also pointed out that evaluating dental trauma outcomes in an *in vivo* model has significant methodological and ethical implications. This is particularly true for the evaluation of the very sensitive therapeutic treatment of revascularization on an immature MCI studied by Bucchi et al (28). The root dentin was divided into two parts to simulate the immature state after the therapeutic procedure of revascularization: a part with thin walls and missing root apex at Cvek stage 4 and a part with newly formed intracanal tissue (mechanical parameters of dentin or cementum), with the root apex classified as 20% of the root length. Accordingly, dental immaturity was presented at stage 4 of the Cvek classification (7): a widely opened apical foramen and almost complete root length. Unfortunately, as in previous studies, values for dentin wall thickness were not reported for all stages of root development.

After reviewing the literature, we decided to use a CBCT of an intact young MCI to reconstruct a basic 3D model since it provided the most accurate data but still required measurements of the dentin wall thickness of the MCI to reconstruct models of different stages of root development in the programme. For this reason, we measured DWT on intraoral periapical radiographs of maxillary incisors of chil-

đenoga sjekutića, a zatim bi se dodatni modeli konstruirali u programu ili izravno na izvađenom sjekutiću prema traženim svojstvima zuba.

Khadar i suradnici (24) upotrijebili su ekstrahirane MSS-e koje su dodatno instrumentirali za simulaciju nezrelih sjekutića s tankim stijenkama dentina i otvorenim apeksom. Nakon instrumentacije korijena (MAF # 80) apikalni otvor dodatno je povećan na 1 mm Peesovim svrdlima kako bi se definirala općenito nezrelost zuba. Eram i suradnici (25) također su pripremili ekstrahirani MCI prije nego što su ga podvrgnuli CBCT pregledu za simulaciju nezrelog sjekutića prema Cvekovu trećem stadiju (7). Korijen je apikalno skraćen za 4 mm (dužina zuba 21 mm, a dužina korijena 9 mm). Nakon instrumentacije korijena (MAF # 80), otvoreni apeks proširen je Peesovim svrdlima za 1 mm preko apeksa na 1,7 mm. Omjer korijenskog kanala bio je približno 1 : 1 u meziodistalnoj dimenziji na CCS-u. Te dimenzije bile su veće od naših u trećem stadiju razvoja korijena: širina apeksa 1,490 ± 0,244 mm i omjer korijena i kanala na CCS-u 1 : 1,19, osim prosječne dužine korijena koja je u našem istraživanju iznosila 11,0 mm. U istraživanju koje su proveli Anthrayose i suradnici (26) CBCT snimke trajnih maksilarnih središnjih sjekutića i podatci iz dostupne literature korišteni su za simulaciju nezrelog MSS modela u Cvekovu trećem stadiju u programu, s apikalnim otvorom od 1,67 mm i dužinom korijena približno 3 mm manjom nego kod zreloga zuba, tj. 10,5 mm, što je više odgovaralo našim mjerenjima. To je istraživanje također imalo protokol sličan našemu, ali je opisan samo jedan stadij razvoja korijena te njegove dimenzije. U istraživanju A. C. Dezzen-Gomide i suradnika (27) opisana su tri različita stadija razvoja korijena za MSS: potpuna rizogeneza, nepotpuna rizogeneza u apikalnoj trećini korijena i nepotpuna rizogeneza u srednjoj trećini korijena. Model potpune rizogeneze temelji se na CBCT-u izvađenog sjekutića. Dva modela nepotpune rizogeneze modificirana su na temelju anatomskih referencija sa šest CBCT snimki nezrelih MSS-a (pacijenti u dobi od 7 do 12 godina) u različitim fazama rizogeneze, ali bez opisa dobivenih vrijednosti. A. C. Dezzen-Gomide i suradnici također su istaknuli kako procjena ishoda dentalne traume u modelu *in vivo* ima značajne metodološke i etičke implikacije. To se osobito odnosi na procjenu vrlo osjetljivoga terapijskog postupka revaskularizacije na nezrelomu MSS-u što su proučavali Bucchi i suradnici (28). U njihovu istraživanju korijenski dentin bio je podijeljen na dva dijela kako bi se simuliralo nezrelo stanje poslije terapijskog postupka revaskularizacije: dio s tankim stijenkama i nedostatnim apeksom u Cvekovu četvrtom stadiju i dio s novoformiranim intrakanalnim tkivom (mehanički parametri dentina ili cementa) s apeksom klasificiranim kao 20 % dužine korijena. U skladu s tim dentalna nezrelost bila je prikazana u četvrtom stupnju Cvekove klasifikacije (7): široko otvoren apikalni foramen i gotovo potpuna dužina korijena. Nažalost, kao i prethodna istraživanja, vrijednosti za debljinu stijenke dentina nisu prikazane za sve stadije razvoja korijena.

Nakon pregleda literature odlučili smo upotrijebiti jedan CBCT intaktnoga mladog MSS-a za rekonstrukciju osnovnog 3D modela kako bismo dobili najpreciznije podatke, ali je za rekonstrukciju ostalih modela faza razvoja korijena u dren aged 7 to 11 years to obtain data for all stages. DWT was measured at three reference lines: at a distance of 1 mm from the apex, 4 mm from the apex, and at the cervical line, as these areas are considered predictors of stress (34, 38). The reference line at 4 mm was of particular interest as further studies will examine the influence of therapeutic treatment, i.e. different post and core systems placing 4 mm gutta-percha apically. Our main objective was to determine if we could use the mean values of the selected parameters for the 5 groups of MCI developmental stages for FEA modelling. No significant deviation from a normal distribution was found. There were statistically significant differences between the developmental stages for parameters L and M, while no significant differences were found for parameter K, as the numerical value of the total root width at the cervical line is always constant in all developmental stages and only the values of dentin thickness and pulp width are the one variable. Most correlations between parameters were statistically significant and consistent with root development anatomy. It is also expected that the differences between the correlations will be reflected in the load distribution of the FEA model. Further investigation of different therapeutic treatments following dental trauma in MCI in relation to the root development stage will contribute to a better understanding of treatment failure. Any information or guidance that can help keep MCI in the oral cavity longer is extremely valuable for both clinicians and patients.

The present study has some limitations. Since there are very few studies on this subject, the average values for the length of maxillary incisors with complete root development were based on the general population. In this macroscopic approach of the finite element method, all measurements were performed by a single person to minimize errors. Considering the 137 radiographs of different patients and their individual anatomy, it was not easy to identify the same angle of the radiograph. Also, the recognition of reference points was difficult. However, according to Plascencia et al (39), the intra- and interobserver agreement provided reliable results in the radiographic assessment of different stages of root development using the Cvek classification. As previously mentioned, the two-dimensional dentin wall thickness data from the intraoral radiographs could be used for 3D modelling of MCI. However, better properties would be obtained by using 137 CBCT images, which is ethically questionable in children. Finally, there were no data in the literature to which we could refer and compare our results.

Conclusion

Despite the limitations of this study, the mean values of the selected parameters for the 5 groups of developmental stages of the maxillary central incisor could be used to model dentin wall thickness using finite element analysis (FEA). However, further research is needed.

programu ipak bilo potrebno mjerenje debljine stijenke dentina s obzirom na različit stadij razvoja korijena. DDZ je mjeren na oralnim periapikalnim rendgenskim slikama maksilarnih sjekutića djece u dobi od 7 do 11 godina kako bi se dobili podatci za sve stadije. DDZ je mjeren na trima referentnim (horizontalnim) linijama: 1 mm od apeksa (M), 4 mm od apeksa (L) te na razini cervikalne linije (K) jer se ta područja smatraju prediktorima stresa (34, 38). Referentna linija 4 mm od apeksa bila je posebno važna zato što će se u budućim istraživanjima ispitivati utjecaj terapijskih postupaka, tj. različitih sustava kolčića i jezgre kod kojih se apikalno ostavlja 4 mm gutaperke. Glavni cilj ove pilot-studije bio je ustanoviti možemo li se koristiti srednjim vrijednostima odabranih parametara za 5 skupina razvojnih stadija MSS-a za MKE modeliranje. Vrijednosti uglavnom nisu značajno odstupale od normalne distribucije. Za parametre L i M postoje statistički značajne razlike između razvojnih faza, a za parametar K nema značajnih razlika jer je numerička vrijednost ukupne širine korijena na cervikalnoj liniji uvijek konstantna u svim razvojnim fazama, a samo su vrijednosti debljine dentina i pulpe varijabilne. Većina korelacija između parametara bila je statistički značajna i u skladu s anatomijom razvoja korijena. Također se očekuje da će se razlike između korelacija odraziti na raspodjelu opterećenja unutar MKE modela. Daljnje istraživanje različitih terapijskih postupaka poslije dentalne traume kod MSS-a u odnosu prema stadiju razvoja korijena pridonijet će boljem razumijevanju neuspjeha u liječenju. Svaka informacija ili smjernica koja može pomoći da se MSS dulje zadrži u usnoj šupljini iznimno je vrijedna i za kliničare i za pacijente.

Ova studija ima neka ograničenja. Budući da postoji vrlo malo istraživanja o toj temi, prosječne vrijednosti za dužinu maksilarnih sjekutića s potpuno razvijenim korijenom temeljene su na općoj populaciji. U ovom makroskopskom pristupu metode konačnih elemenata sva mjerenja obavila je jedna osoba kako bi se pogreške svele na minimum. Uzimajući u obzir 137 radiografija različitih pacijenata i njihovu individualnu anatomiju, nije bilo lako identificirati isti kut na snimkama i prepoznavanje referentnih točaka, ali prema Plascenciji i suradnicima (39) podudarnost unutar promatrača i između njih dala je pouzdane rezultate u radiografskoj procjeni različitih faza razvoja korijena s pomoću Cvekove klasifikacije. Kao što je ranije spomenuto, dvodimenzionalni podatci o debljini stijenke dentina iz intraoralnih radiografija mogu se koristiti za 3D modeliranje MSS-a, no bolja obilježja postigla bi se pregledom 137 CBCT-a, što je kod djece etički vrlo upitno. Konačno, u literaturi nije bilo podataka na koje bi se mogli odnositi i s kojima bi se mogli usporediti naši rezultati.

Zaključak

Unatoč ograničenjima ove studije, srednje vrijednosti odabranih parametara debljine zubnog korijena za 5 skupina razvojnih stadija gornjega središnjeg sjekutića mogu se koristiti za modeliranje debljine dentinskoga zida s pomoću analize konačnih elemenata, no potrebna su daljnja istraživanja.

Conflict of interest statement

The authors declare no conflict of interest.

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Doprinos autora: **P. B. S. –** glavni istraživač, koncept i dizajn istraživanja, pregled literature, prikupljanje podataka, metodologija i mjerenje, interpretacija i pisanje teksta; **J. L. H. –** interpretacija i analiza uzoraka, softvare; **T. J. L. –** nadzor i tehnička podrška; **N. B. –** pretraživanje literature i tehnička obrada podataka; **H. J. –** glavni mentor, pregled i uređivanje, nadzor

Sažetak

Cilj: Željela se odrediti prosječna debljina dentinskoga zida (DDZ) maksilarnog središnjeg sjekutića (MSS) potrebna za izradu modela razvoja korijena metodom konačnih elemenata (MKE). **Materijal i metode**: Pregledano je ukupno 137 intraoralnih periapikalnih rendgenskih slika MSS-a djece u dobi od 7 do 11 godina koje su zatim bile podijeljene u 5 skupina prema stadijima razvoja korijena, a uključivale su stadije u kojima je razvijena jedna polovina korijena zuba (S1), tri četvrtine korijena zuba (S2), više od tri četvrtine korijena zuba (S3), potpuno razvijeni korijen s otvorenim apeksom (S4) te potpuno razvijeni korijen sa zatvorenim apeksom (S5). DDZ je mjeren na trima referentnim (horizontalnim) linijama – 1 mm od apeksa (M), 4 mm od apeksa (L) te na razini cervikalne linije (K). Izmjerena je debljina distalnoga zida dentina (M1, L1 i K1), debljina pulpe (M2, L2 i K2), debljina mezijalnog zida dentina (M3, L3 i K3) i debljina apikalnog otvora (N) u dijagnostičkom softveru Soredex Scanora 5.1.2.4. U statističkoj analizi uspoređene su vrijednosti parametara K, L i M između pojedinih razvojnih stadija (multivarijatna ANOVA) te linearne korelacije između parametara (Pearsonova korelacijska analiza). Sve analize provedene su na razini značajnosti $\alpha = 0,05$. **Rezultati**: Parametri L i M statistički su se značajno razlikovali između razvojnih stadija, a za parametar K nisu opažene značajne razlike. Većina korelacija između parametara bila je statistički značajna, a vrijednosti Pearsonova koeficijenta korelacije $R > 0,6$ smatrane su praktički značajnima. Svi parametri za debljinu dentinske stijenke prema distalno i mezijalno te za debljinu kanala uzajamno su dobro korelirali na svojoj referentnoj liniji ($R = 0,46 – 0,68$), a nisu statistički značajno korelirali s ukupnom debljinom na svojoj referentnoj liniji (parametri K, L ili M), osim parametra K3 ($R = 0,42$). **Zaključak**: Unatoč ograničenjima ove studije, srednje vrijednosti odabranih parametara debljine zubnog korijena za 5 skupina razvojnih stadija gornjega središnjeg sjekutića mogu se koristiti za modeliranje debljine dentinskoga zida.

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