IDR International Dental Research

Int Dent Res 2024; 14(3): 93-104
https://doi.org/10.5577/idr2024.514

Original Article Open Access

Evaluation of biomechanical effects of different treatment procedures and materials used in teeth with incomplete root development using finite element analysis

Elif Aslan[1], **Buket Ayna**[2]

[1] Mardin Oral and Dental Health Center, Mardin, Türkiye

[2] Dicle University, Faculty of Dentistry, Department of Pediatric Dentistry, Diyarbakır, Türkiye

Received: 23 September 2024

Accepted: 26 November 2024

Correspondence:

Dr. Elif ASLAN
Mardin Oral and Dental Health Center, Mardin, Türkiye
E-mail: elfasln@msn.com

How to cite this article:

Aslan E, Ayna B. Evaluation of biomechanical effects of different treatment procedures and materials used in teeth with incomplete root development using finite element analysis. Int Dent Res 2024;14(3):93-104. https://doi.org/10.5577/intdentres.514

Abstract

Aim: The purpose of the present study is to evaluate, using finite element analysis (FEA), the stresses generated by the applications of partial pulpotomy, apexification, and regenerative endodontic procedure (REP), as well as the materials that can be used in these treatment procedures—calcium hydroxide (CH), mineral trioxide aggregate (MTA), BioAggregate (BA), and Biodentine (BD)—under functional forces on models of teeth having incomplete root development.

Methodology: A maxillary incisor tooth model with complete root development and surrounding tissues was created three-dimensionally, utilizing tomography data in a computer environment. Based on this model, two healthy tooth models with complete and incomplete root development were created. In addition, 17 treatment procedure models were simulated, performing the applications of partial pulpotomy, apexification, and REP, using the materials CH, MTA, BA, and BD. Von Mises stress values that were generated in the tooth by applying functional mastication force were examined with FEA in three regions: apical, middle, and cervical. The results were evaluated using Altair Evolve structural analysis software and taking Von Mises criteria into consideration while the stress value range was limited from 0 to 10+ MP.

Results: Completion of root development decreased the stresses in the teeth that had incomplete root development. In the partial pulpotomy models, the stresses that formed in the teeth decreased after completion of apexogenesis, and once again, completion of root development by formation of cement-like tissue following REP decreased the stresses that formed in the teeth. The highest stress values were detected in the apical and middle root regions of the models that simulated apexification, compared to other models. The evaluations of the materials used in these treatment procedures revealed that the highest stress values formed in the models that simulated the use of CH. MTA, BioAggregate, and Biodentine generated similar levels of stress, whereas the lowest level of stress was generated in the model that applied MTA.

Conclusion: The selection of treatment procedures that stimulate root development is helpful in reducing stresses generated in teeth that have incomplete root development. Treatment models performed using MTA strengthened the tooth structure more than treatments performed using CH, BA, or BD.

Keywords: Partial pulpotomy, apexification, finite element analysis, Mineral Trioxide Aggregate, Biodentine, BioAggregate

Introduction

The accurate determination of root development stages is very important in the selection of diagnostic and therapeutic options for injuries of permanent teeth that have incomplete root development involving pulp (1). The erupted permanent teeth most commonly complete 60%-80% of their root development (2). The developing roots of the teeth with incomplete root development have open apexes during the 2-3 years following eruption. This stage is the period in which particularly traumatic dental injuries (TDIs) are most commonly seen in children. In addition, caries in children with poor oral hygiene may lead to pulpal inflammation, loss of vitality, and cessation of root development by rapid progression, due to incomplete root development after eruption and the large size of the pulp chambers (3,4).

If pulpal inflammation has affected pulp tissue in a way that is reversible, the vitality of the pulp can be preserved by performing vital pulp treatment techniques such as indirect pulp capping, direct pulp capping, partial pulpotomy, and total pulpotomy. This allows the function of tooth to be maintained. Self-protection of the pulp after inflammation and recovery of pulpal health alongside regression of inflammation through the provision of the appropriate conditions are required for continuous root development(5).

Partial pulpotomy is a vital pulp treatment technique that aims to remove the infected part of the coronal pulp and to protect the vitality of the remaining coronal and root pulp. It can be applied in conditions that allow for the control of pulpal bleeding within a few minutes for exposed pulp resulting from caries or trauma in permanent teeth with incomplete root development. This treatment should be applied in vital teeth, and pulp should be healthy or at the stage of reversible pulpitis(6). CH, MTA, and tricalcium silicate-based materials can be used in partial pulpotomy(4).

When root canal treatment (RCT) is needed because of a loss of root vitality due to deep dentinal caries or traumatic dental injuries (TDIs) in teeth with incomplete root development, thin root canal walls and a very wide apex complicate RCT. For successful RCT, root canals should be hermetically obturated three-dimensionally, which is possible only when there is full apical closure. Therefore, for performing RCT, the procedures that stimulate apical formation should be primarily applied to incomplete teeth(1,7,8). Many techniques have been recommended for the treatment of teeth with incomplete root development that require RCT. The most commonly used techniques are apexification and revascularization treatments.

Even though some difficulties related to RCT for teeth with incomplete root development are manageable through traditional apexification(9) and one-session apexification(10) techniques, the risk of root fracture formation because of a poor crown-root ratio remains. A retrospective clinical study conducted by Cvek(11) found that teeth with incomplete root development had a higher rate of cervical root fractures compared to teeth with complete root development. It has also been reported that the incidence of fractures ranges between 28% and 77%, depending on the level of root development. This fact has directed clinicians to research novel procedures that result in pulp regeneration, dentine formation, and root development after treatment. It has been shown that the formation of new vascularized tissue can be induced in the apical triple region of the root canals of teeth with incomplete root development including a necrotic pulp and apical lesion which were applied endodontic treatment by applying REP that was first introduced in the literature at the beginning of 1960s. This procedure, which is known as revascularization today, is based on providing blood supply into the root canal from preapical tissues or intracanal vital tissues and hermetically sealing the root canal by forming a barrier using a calcium-silicate containing material in the coronal part of the root on the forming blood clot following disinfection of the root canal by irrigation agents and antimicrobial pastes prior to mechanical preparation of the root canal (12-14).

After vital and nonvital treatments were applied to teeth and periodontal tissue, functional, parafunctional, and traumatic forces, along with the materials used in the treatments, caused stress formation in these regions. The vitality of pulp, the application site, and the biomechanical characteristics of the materials influence the amount of stress that forms in partial pulpotomy, apexification, and REP treatments (15, 16).

In order to evaluate the biomechanical characteristics of the materials used in dentistry and to assess the stresses on dental structures, conducting stress analysis on these structures has become very widespread in recent years. The determination of the mechanical characteristics, stresses, and tensile strengths of the materials used against the functional forces play a key role in achieving a successful restoration (16, 17). Finite element analysis (FEA) is a computer-based quantitative analysis method that can be employed as an acceptable approach to solve various mechanical problems. Conducting stress analysis to determine how living organisms and organs behave against the forces is very difficult, costly, risky, and usually impossible (18). Therefore, stress analysis studies should be performed on models that simulate the living tissues.

The purpose of this study is to evaluate partial pulpotomy, one-session apexification, and REPs treatments performed after pulpal injury caused by trauma or caries in teeth with incomplete root development to help determine how much stress occurs, which regions of the teeth are impacted, and the effect of the materials used in these treatments under the functional forces of FEA. This analysis aims to provide information about the stresses generated by treatment techniques under functional forces in the clinical environment and the preferred materials to be applied to teeth with incomplete root development. The study will also offer guidance for the selection of treatment techniques and materials.

Materials and Methods

This study was approved by the Local Ethics Committee of Dicle University, Faculty of Dentistry (Decision no: 2021/16). A dental tomographic image with a slice thickness of 0.2 mm of an 18-year-old patient taken from the archive of Tinus Engineering was utilized for the study.

In the study, the model was obtained from tomography device data (HiRes3D- Plus; Largev, Beijing, China) using 3DSlicer software. Reverse engineering and three-dimensional CAD activities were performed using ALTAIR Evolve software, while ALTAIR Hypermesh software was employed for optimization of solid materials for analysis of environmental and construction activities of optimized meshwork (Figs. 1, 2). The Nastran-based Altair Optistruct (Altair, Troy, MI, USA) implicit solver was used for the simulated finite element models (Fig. 3).

A model of a permanent maxillary central tooth with complete root development was obtained by tomography (Model 1). A second model, based on the structure of the first model, was created to simulate a tooth with incomplete root development with 20% root apex and dentine wall thickness according to the fourth stage of Cvek's classification (Model 2). Subsequently, the structure of the model with incomplete root development was used to create 17 additional models to simulate the following conditions.

Model 3: Tooth model with complete, permanent restoration by simulating the tooth with incomplete root development, performing partial amputation using 2 mm CH.

Model 4: Tooth model with complete, permanent restoration by simulating the tooth with incomplete root development, performing partial amputation using 2 mm MTA.

Model 5: Tooth model with complete, permanent restoration by simulating the tooth with incomplete root development, performing partial amputation using 2 mm BA

Model 6: Tooth model with complete, permanent restoration by simulating the tooth with incomplete root development, performing partial amputation using 2 mm BD.

Model 7: The state of Model 3 with complete root development.

Model 8: The state of Model 4 with complete root development.

Model 9: The state of Model 5 with complete root development.

Model 10: The state of Model 6 with complete root development.

Model 11: Tooth model with complete, permanent restoration by simulating the tooth with incomplete root development, performing apexification using 4 mm MTA.

Model 12: Tooth model with complete, permanent restoration by simulating the tooth with incomplete root development, performing apexification using 4 mm BA.

Model 13: Tooth model with complete, permanent restoration by simulating the tooth with incomplete root development, performing apexification using 4 mm BD.

Model 14: Tooth model with complete, permanent restoration by simulating the tooth with incomplete root development, performing REP using 3 mm MTA.

Model 15: Tooth model with complete, permanent restoration by simulating the tooth with incomplete root development, performing REP using 3 mm BA.

Model 16: Tooth model with complete, permanent restoration by simulating the tooth with incomplete root development, performing REP using 3 mm BD.

Model 17: The state of Model 14 with complete root development.

Model 18: The state of Model 15 with complete root development.

Model 19: The state of Model 16 with complete root development.

Elastic modulus and Poisson's ratios of the materials used in the models were shown in Table 1, while the simulations of the models were presented in Figures 2, 3.

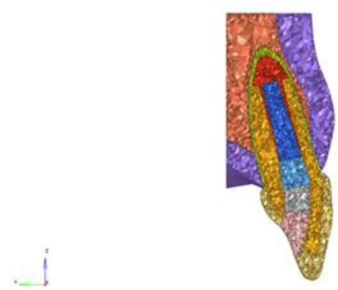


Figure 1. Meshing state of the tooth model

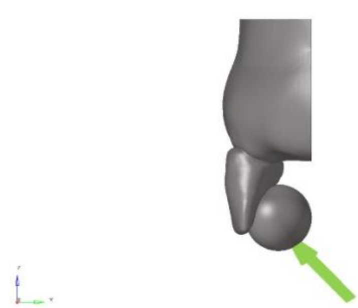


Figure 2. Palatinal force applied by a steel ball

Table 1. Elastic modulus of the materials (16, 19-24)

Material	Elastic Modulus [MPa]	Poisson's Ratio	Color
Enamel (19)	84.100	0.30	
Dentin (19)	18.600	0.31	
Cement (20)	8.150	0.30	
Pulp (16)	3	0.45	
Periodontal Lig. (19)	68.9	0.45	
Cortical Bone (19)	13.700	0.30	
Trabecular Bone(19)	1.370	0.30	
CH (21)	48.000	0.35	
MTA (16)	11.760	0.314	
Bioaggregate (22)	26.000	0.25	
Biodentine (16)	22.000	0.33	
Gutta-Percha (23)	140	0.45	
RMCIS (24)	10.860	0.30	
Composite (25)	18.600	0.28	
Foodstuff-Steel Balls	200.000	0.30	

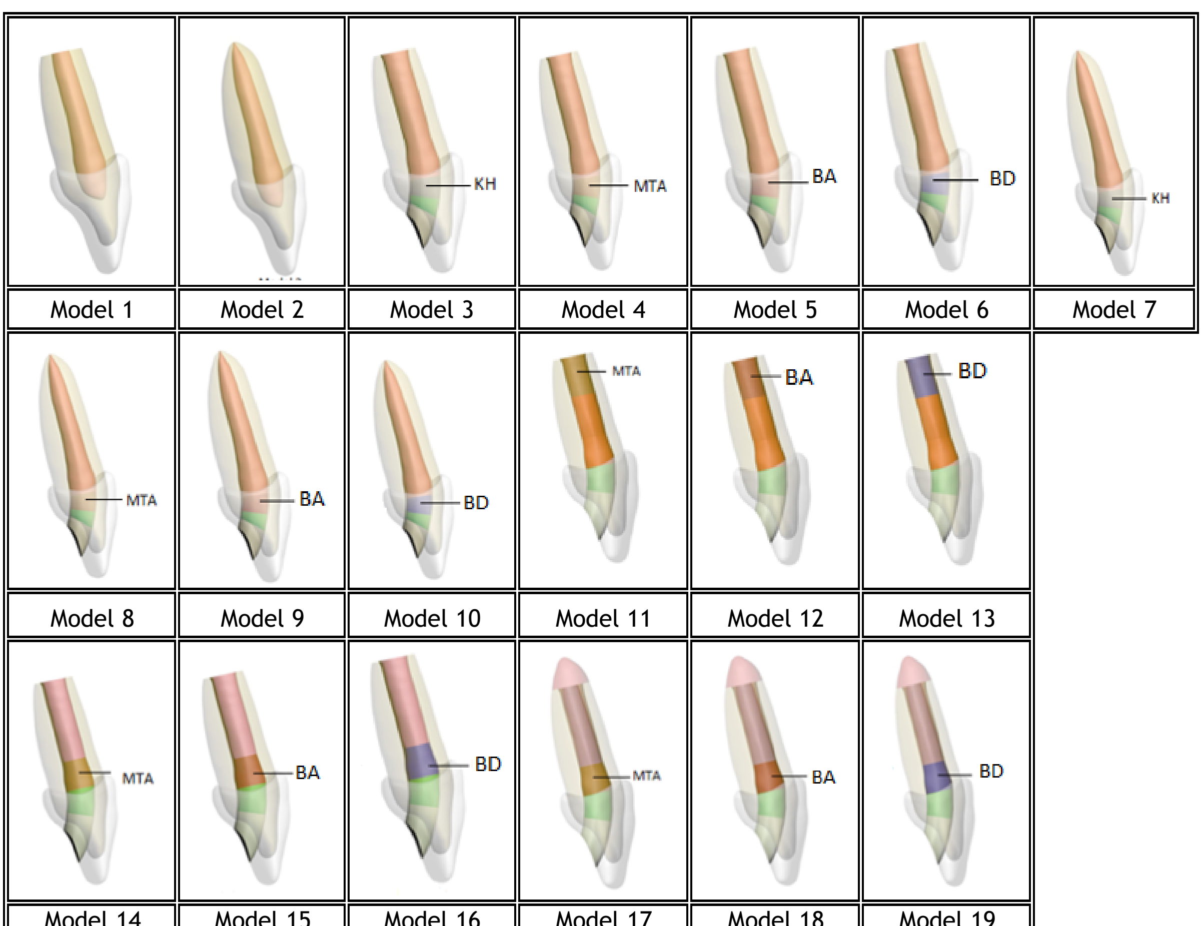
It was assumed that all the materials and structures had homogeneous, isotropic, and linear elasticity. Table 1 shows the elastic properties of the materials, as obtained from the literature. A 100 N force was applied to the longitudinal axis of the tooth with an angle of 45 degrees over a round-shaped object from the cingulum region of the tooth. This mimics the functional mastication force on the models in the calculation of stress models (Fig. 2). The results were presented in accordance with the von Mises criteria. The calculated numerical data were converted to colorful graphics to aid the visualization of the mechanical conditions in the models.

Results

The models were created, and the application of stress was performed as determined. The model-based section images of the stress distribution that formed following the application of stress were analyzed (Figures 4-9).

Table 2 and Graphic 1 (Figure 10) show the maximum von Mises stress values (MPa). The processed root regions of the models were divided into three equal portions (cervical, middle, and apical regions) to assess their maximum von Mises stress values.

Figure 3. Models and the materials used in the applications



Stresses increased in the roots of the tooth models that were amputated using CH. MTA sealing was associated with lower stress compared with BA and BD sealings (Figs. 6, 7).

Compared to other models, the highest stress values were found in the models in which MTA, BA, and BD materials were used for apexification. However, lower values were detected with MTA, which is considered to support dental tissues better than BA or BD (Fig. 8). Compared to the models with complete root development, higher stress values were encountered in the models with incomplete root development that were simulated with partial amputation and REP treatments (Figs. 6, 9). It was observed in the REP and apexification models evaluated for comparison between nonvital endodontic treatments that regeneration treatment, which stimulates the completion of root development, generated lower stresses (Figs. 8, 9, 11). In the comparison between partial amputation as a vital dental treatment and treatments applied to nonvital teeth without regard to which material (CH, MTA, BA, or BD) was used, it was found that stresses were distributed more appropriately in the models simulated with partial amputation (Figs. 6-9, 11).

Intramaterial Stresses

The evaluation between the materials regarding generated stresses showed that the lowest stress was generated by MTA (Table 3, Fig. 12), followed by BD, BA, and CH (Figs. 11, 13-16).

Table 2. Stress values forming in the models (apical-middle-cervical).

Model	Treatment	Material	Apical	Middle	Cervical
Model 1	Health tooth-OA	N/A	33.38	28.09	44.06
Model 2	Health tooth-OA	N/A	1195	24.89	41.62
Model 3	Partial pulpotomy-OA	CH	35.80	28.70	49.57
Model 4	Partial pulpotomy-OA	MTA	35.80	28.71	49.19
Model 5	Partial pulpotomy-OA	Bioaggregate	35.80	28.70	49.35
Model 6	Partial pulpotomy-OA	Biodentine	35.80	28.70	49.29
Model 7	Partial pulpotomy-OA	CH	13.37	26.39	48.50
Model 8	Partial pulpotomy-CA	MTA	13.36	25.77	48.35
Model 9	Partial pulpotomy-CA	Bioaggregate	13.36	26.33	48.41
Model 10	Partial pulpotomy-CA	Biodentine	13.36	25.77	48.40
Model 11	Apexification	MTA	39.65	29.49	58.02
Model 12	Apexification	Bioaggregate	40.45	29.65	58.02
Model 13	Apexification	Biodentine	40.29	29.61	58.02
Model 14	REP-OA	MTA	36.97	27.95	53.35
Model 15	REP-OA	Bioaggregate	37.05	28.44	53.76
Model 16	REP-OA	Biodentine	37.02	28.10	53.66
Model 17	REP-CA	MTA	13.65	26.11	53.32
Model 18	REP-CA	Bioaggregate	13.69	26.47	53.62
Model 19	REP-CA	Biodentine	13.65	26.37	53.41

Table 3. Maximum stress values generated in the materials used in the models.

Model	Treatment	Material	Stress value (MPa)
Model 3	Partial pulpotomy-OA	CH	41.68
Model 4	Partial pulpotomy-OA	MTA	15.01
Model 5	Partial pulpotomy-OA	Bioaggregate	30.03
Model 6	Partial pulpotomy-OA	Biodentine	24.67
Model 7	Partial pulpotomy-CA	CH	35.21
Model 8	Partial pulpotomy-CA	MTA	13.95
Model 9	Partial pulpotomy-CA	Bioaggregate	26.35
Model 10	Partial pulpotomy-CA	Biodentine	24.50
Model 11	Apexification	MTA	14.41
Model 12	Apexification	Bioaggregate	28.88
Model 13	Apexification	Biodentine	23.70
Model 14	REP-OA	MTA	10.04
Model 15	REP-OA	Bioaggregate	21.68
Model 16	REP-OA	Biodentine	18.42
Model 17	REP-CA	MTA	10.48
Model 18	REP-CA	Bioaggregate	22.87
Model 19	REP-CA	Biodentine	19.33

a b

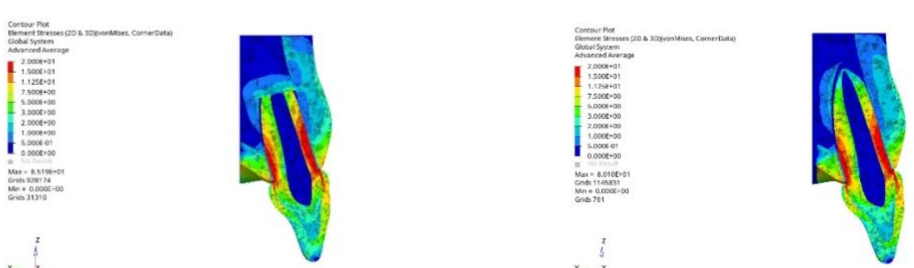


Figure 4. The stress distributions of Models 1 and 2 (a: Model 1, b: Model 2)

a b c d

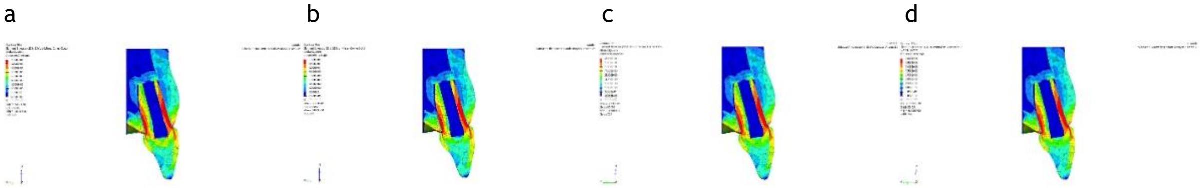


Figure 5. The stress distributions of Models 3-4-5-6 (a: Model 3, b: Model 4, c: Model 5, d: Model 6)

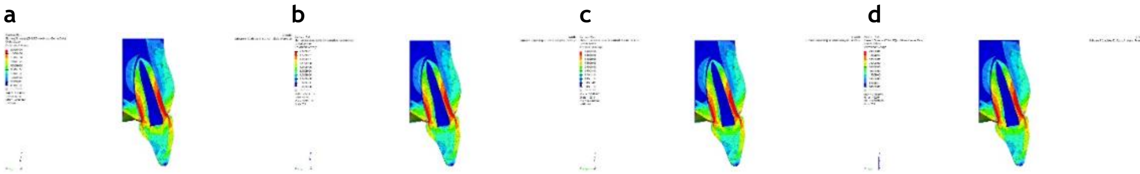


Figure 6. The stress distributions of Models 7-8-9-10 (a: Model 7, b: Model 8, c: Model 9, d: Model 10)

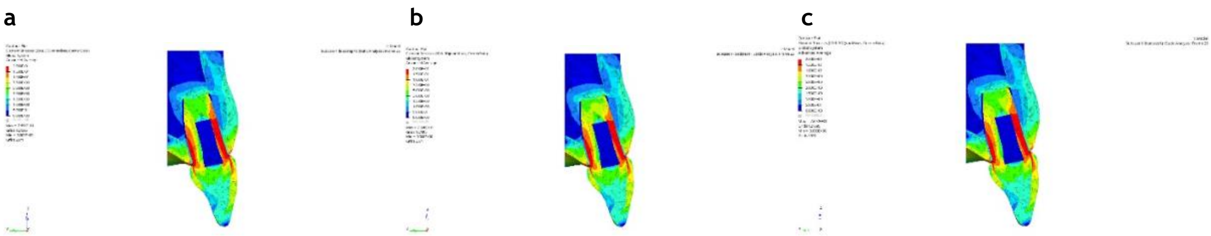


Figure 7. The stress distributions of Models 11-12-13 (a: Model 11, b: Model 12, c: Model 13)

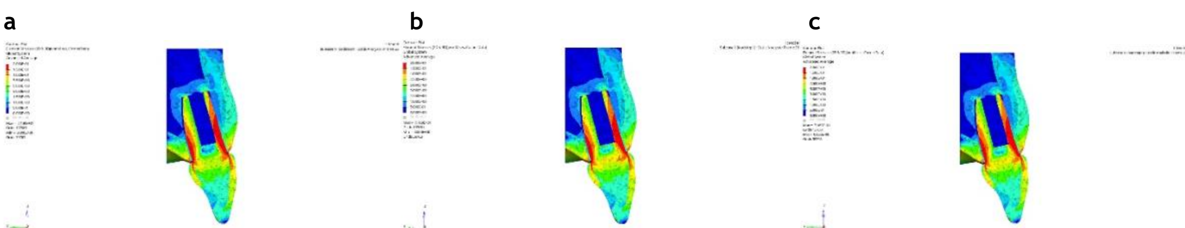


Figure 8. The stress distributions of Models 14-15-16 (a: Model 14, b: Model 15, c: Model 16)

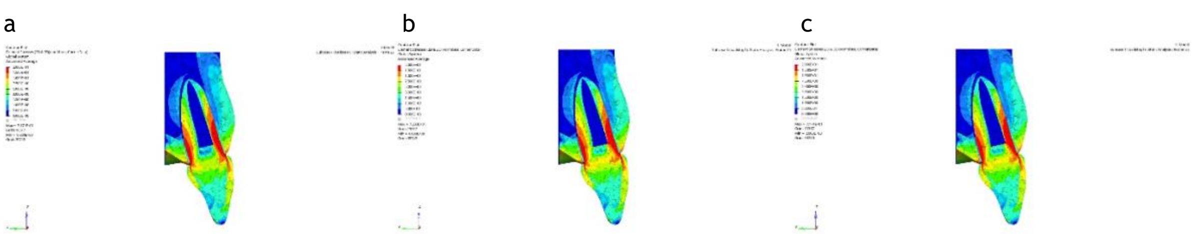


Figure 9. The stress distributions of Models 17-18-19 (a: Model 17, b: Model 18, c: Model 19)

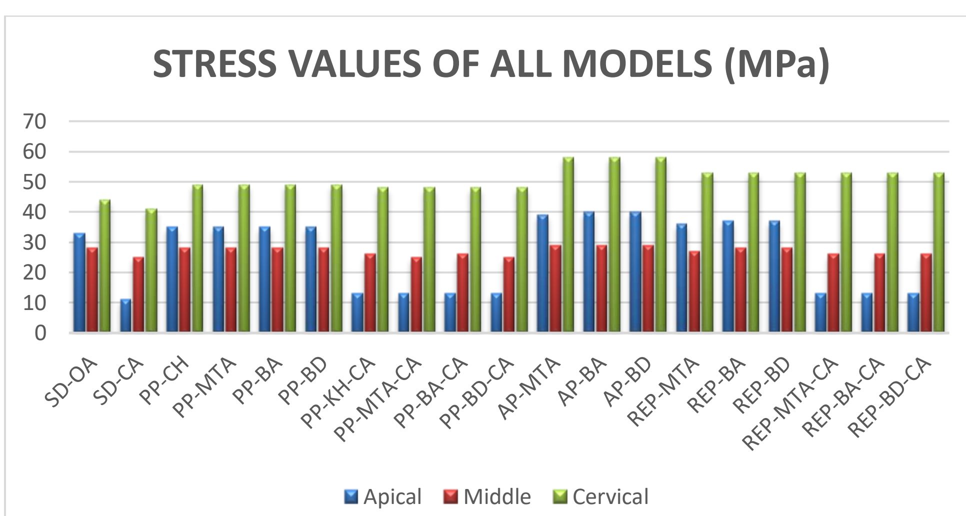


Figure 10. Stress values in the apical, middle and cervical regions of all models (PP: Partial pulpotomy, AP: Apexification, OA: Open apex, CA: Closed apex, BA: Bioaggregate, BD: Biodentine).

Int Dent Res 2024; 14(3): 93-104

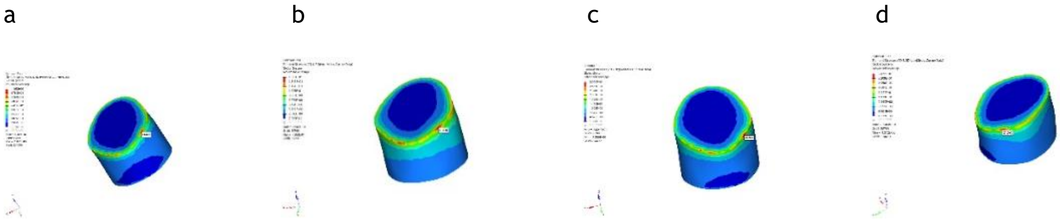


Figure 11. Intra-material stress distribution of Models 3-4-5-6 (a: Model 3, b: Model 4, c: Model 5, d: Model 6)

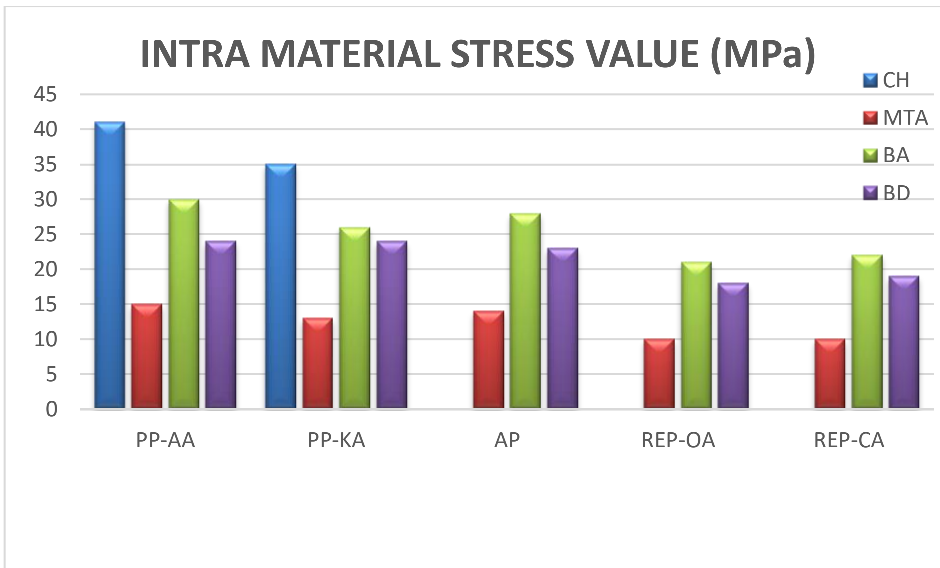


Figure 12. The intra-material stress values of all models (PP: Partial pulpotomy, AP: Apexification, OA: Open apex, CA: Closed apex, BA: Bioaggregate, BD: Biodentine)

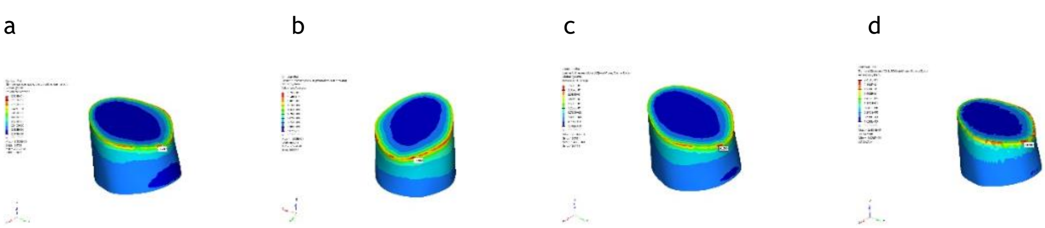


Figure 13. Intra-material stress distribution of Models 7-8-9-10 (a: Model 7, b: Model 8, c: Model 9, d: Model 10)

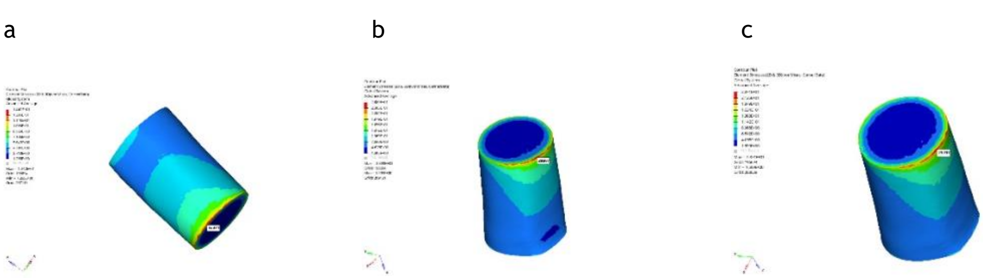


Figure 14. Intra-material stress distribution of Models 11-12-13 (a: Model 11, b: Model 12, c: Model 13)

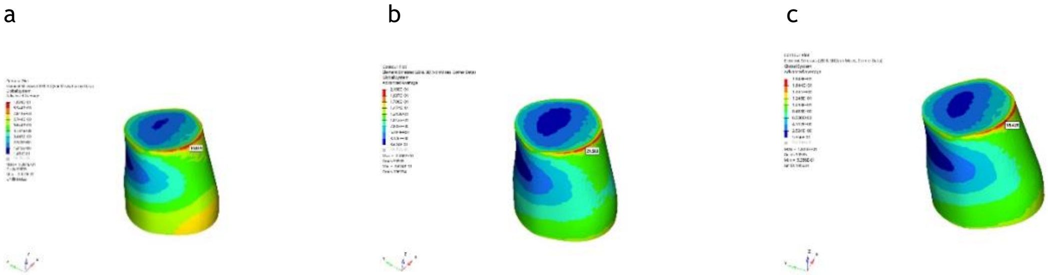


Figure 15. Intra-material stress distribution of Models 14-15-16 (a: Model 14, b: Model 15, c: Model 16)

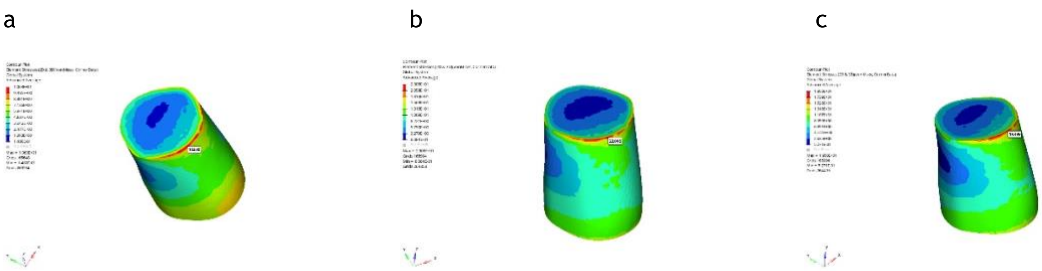


Figure 16. Intra-material stress distribution of Models 17-18-19 (a: Model 17, b: Model 18, c: Model 19)

Discussion

According to the results of this study, treatment protocols and the materials used in these treatment protocols change stress values and distributions. As a consequence, the hypothesis that different treatment protocols and materials have different effects on stress values and distributions can be accepted.

Principal stress values can be used to evaluate the analysis results for fragile materials while von Mises stress values can be used for ductile materials. In many analyses, von Mises stresses are preferred because they provide information about stresses throughout the structure and indicate the probability that damage will occur. For these reasons, we preferred to evaluate von Mises stresses for the models created in our study.

According to the study results, the highest stress values were found in the cervical region of the root dentin in the models with incomplete root development. Because the crown-to-root ratio changes due to the completion of root development, the fracture resistance against functional forces changed in the apical, middle, and cervical regions. Similarly, Anthrayose et al. (26) and Çetinsaya et al. (27) used FEA to analyze tooth models with complete and incomplete root development. These studies have reported that lower levels of stress were generated in the teeth with complete root development. Based on this information, it can be proposed that increasing root length and thickening thin dentin walls results in decreased stresses and a more balanced stress distribution.

The stress generated in the apical part of the tooth decreased at a rate of approximately 60% upon the completion of apexogenesis in the partial pulpotomy models. A lower rate of reduction was observed in the cervical region, which exhibited the most intense stress formation. Therefore, it can be stated that the stresses generated in the dental tissues decreased after the completion of apexogenesis and were distributed in a more balanced manner. Lower stress generation and a more balanced stress distribution were observed in complete and incomplete models simulated using MTA compared to models simulated using other materials. Stress values generated in models simulated using BA and BD were similar, although slightly higher, to those using MTA. CH was the material that generated the highest level of stress. Thus far, no studies have examined stress distribution after partial pulpotomy. The findings of our study indicated that the stress generated in the tooth can be reduced by changing the crown-root ratio in favor of the root. This can be attributed to apexogenesis and thickening of the dentin walls. These results are similar to those of the study by Belli et al., in which they evaluated different treatment procedures and examined the stresses in models simulating total pulpotomy using

CH, MTA, and Biodentine (16). The presence of vital tissues in the cervical region of the tooth may help increase the fracture resistance of the tooth by facilitating dentin apposition upon completion of root development using the partial pulpotomy technique. Therefore, the tooth demonstrates a balanced stress distribution similar to that in a healthy tooth.

Since root development cannot be stimulated with the apexification technique, the post-treatment values were monitored and analyzed. According to our study results, the stress levels generated in the cervical regions of the models were similar. The stresses generated by the materials used as apical plugs were approximately similar, and the lowest stress values were detected in models using MTA. MTA was applied using BD and BA. Our results are supported by the findings of studies carried out by Belli et al, Eramet al, Özdemir et al, Çetinkaya et al, and Ok et al. to examine models that achieved apexification using FEA (22, 26, 28–30). Belli et al. reported an increase in stress in the apical and middle regions of the root in models that applied the apexification technique (28, 31). In our study, similar stress levels were observed in the cervical regions of the models that applied the apexification technique, and the highest stress intensity was noted after the application of the functional mastication force. This can be explained by the positioning of the materials used in the apical tooth and the fact that gutta-percha used in the cervical region has no structural properties that strengthen the teeth.

In the REP models, two different root development stages were created to simulate (a) the discontinuation of root development as an unexpected condition in the post-treatment period, and (b) the continuance of root. The histological examination revealed new cement-like tissue that facilitates thickening of dentin walls and the closure of apical foramen in cases of continuation of root development after REP. Therefore, in our FEA study, the tissue formed was accepted as cement, and the elastic modulus and Poisson's ratios that define the physical properties of the cement were used.

Unexpected conditions following REP treatments have been defined in the literature. Although symptoms do not appear in teeth under these conditions, expected root development may not occur. These conditions are considered successful even though incomplete root development and intraoral function of the tooth can continue (34). In our study, lower stress values were observed in the models with incomplete root development after REP treatment compared with the apexification models. It was determined that REP generates lower stress than apexification treatment, although root development did not continue in the REP treatment. This condition can be attributed to the fact that tissue under the cervical barrier has a structure similar to that of healthy pulp tissue in REP treatment. Additionally, the apexification models exhibited maximum stress values in the apical, middle, and cervical regions of the tooth compared with all other treatments. Based on these results, it can be suggested that REP treatment is preferable since it generates lower stress values than apexification treatment, although root development does not continue. Given that no other study has compared a condition with discontinuous root development after REP with apexification, and it is considered that studies of this kind direct clinicians to treatments that stimulate root development, similar further studies on this subject are needed. Lower stress values were encountered in the models that applied REP treatment compared with apexification, even in cases with discontinuous root development as an unexpected condition. Therefore, it is notable that REP treatment, which can be performed as an alternative to apexification, increases fracture resistance compared with the apexification technique, although REP treatment offers no predictable results.

The evaluation of the stresses generated in the simulated models showed that healthy tooth models with complete root development generated the lowest stress values. The partial pulpotomy technique providing apexogenesis exhibited the most approximate stress distribution to the healthy tooth. This condition can be explained by dentin appoposition by the impact of healthy pulp in the cervical region, which revealed the most intense stress accumulation. Additionally, it changed the crown–root ratio in favor of the root by the completion of apexogenesis, strengthening the tooth structure and thereby reducing fracture resistance. Similarly, with partial pulpotomy, it was ascertained that the stresses generated in the tooth had a balanced distribution after completion of root development with cement in the REP models, and the stress values were lower than in the models with incomplete root development. In contrast, the apexification models demonstrated the highest stress values in the apical, middle, and cervical regions of the root compared with the other models. This result can be explained by discontinuance of root development in apexification, positioning of the materials in the apical region of the tooth, and the fact that gutta-percha used in the cervical region of the tooth does not structurally support the tooth against stress. In the literature, there is no study that compares partial pulpotomy, apexification, REP applications, and the stresses generated by the materials used in these applications together.

Comparison of the materials utilized in all simulated treatment techniques in our study revealed that models that applied MTA exhibited the lowest stress values, followed by BD, BA and CH, respectively. This suggests that MTA strengthens the tooth structure more effectively compared to other materials. It is essential for materials used in root canal treatments to have similar physical properties to dentin. Tricalcium silicate-based materials, which have been shown to have similar physical properties to dentin, can enhance fracture resistance by distributing stress more evenly under functional loads in endodontically treated roots (35). Studies have evaluated BD and MTA in cases of root fracture, reporting similar results in terms of strengthening the tooth root against fracture (30, 36). Nagaset al. found that BD makes the tooth structure more resistant to fracture compared to MTA (37).

Meanwhile, numerous studies have shown that MTA enhances the resistance of the tooth root against fracture (16, 32, 38). This phenomenon has been attributed to the chemical bond formed by a hydroxyapatite-like layer between MTA and dentin.

In the analysis of stress distribution patterns in dentin, the highest stress values were detected in the one-third portion of the cervical root in all models. This area is particularly susceptible to the development of fracture lines during loading, and this result is consistent with those reported in other FEA studies (16, 29, 32). This susceptibility may be caused by cervical narrowing and the fact that the cervical region functions as an abutment point in the application of mastication force, thereby intensifying stress.

Conclusion

1. Stress levels in healthy teeth with incomplete root development decreased by approximately 60% after the completion of root development, rendering the teeth more resistant to fracture.
2. Comparing the final states of the treatment techniques, partial pulpotomy, which is a vital technique, exhibited the lowest stress values, followed by the REP models with complete root development using cement-like tissue. In the models with incomplete root development, the REP technique yielded lower stress values than the apexification technique.
3. Evaluation of the stresses generated by the materials used in all the treatment techniques revealed the highest stress values in models applying CH. MTA materials provided better support to the tooth structure and generated lower stress values than other materials across all treatment techniques. Although MTA generated stress values comparable to BA and BD, the stress values, from lowest to highest, were MTA, BD and BA.
4. The highest stress values under functional mastication forces were localized in the cervical region of the tooth in maxillary central teeth for all models.
5. FEA studies have limitations because they are based on different assumptions. Thus, it is imperative to support FEA studies with long-term clinical studies.

Disclosures

Ethical Approval: Ethics committee approval was received from the Dicle University Faculty of Dentistry Local Ethics Committee, in accordance the World Medical Association Declaration of Helsinki, with the approval number: 2021-16.

Peer-review: Externally peer-reviewed.

Author Contributions: Conception – E.A.; Design – E.A.; Supervision – B.A.; Materials – E.A., B.A.; Data Collection and/or Processing – E.A., B.A.; Analysis and/or Interpretation – E.A.; Literature Review – E.A.; Writer –E.A.; Critical Review – B.A.

Conflict of Interest: No conflict of interest was declared by the authors.

Funding: This study was supported by Dicle University, Scientific Research Project Coordination Unit. Project Number: SBE.21.013.

References

1. Camp JH., Barrett EJ PF. Pediatric endodontics: endodontic treatment for the primary and young, permanent dentition In: Cohen S, Burns RC, editor. Pathways of the pulp. 8th Ed. CV Mosby Co. 2002;833-9.
2. Bhaskar S, Kumar G. Orban' s Oral Histology and Embryology. 15. baskı. Haryana, India; 2019. 21-37 p.
3. Dean JA. Dental Caries in the Child and Adolescent. In: McDonald And Avery's Dentistry For The Child And Adolescent: Dental Cari. 10. Baskı. Indianapolis, Indiana: Elsevier; 2016. p. 156-77.
4. Welbury R, Duggal M, Hosey MT. Paediatric Dentistry: Operative treatment of dental caries in the young permanent dentition. 5. Baskı. Oxford Universty Press; 2018. 155-183 p. https://doi.org/10.1093/oso/9780198789277.003.0018
5. Ghoddusi J, Forghani M, Parisay I. New approaches in vital pulp therapy in permanent teeth. Iran Endod J. 2013;9(1):15-22.
6. American Academy of Pediatric Dentistry (2020) Guideline on pulp therapy for primary and immature permanent teeth. 2020.
7. Demiriz L, Çetiner S. Nekrotik Pulpalı İmmatür Dişlerde Tedavi Yaklaşımları Treatment Approaches In Immature Teeth With Necrotic Pulp. ADO Klin Bilim Derg. 2011;5(1):770-81.
8. Friend LA. The Treatment of Immature Teeth with Non-vital Pulps. Int Endod J. 1967;1(2):28-33. https://doi.org/10.1111/j.1365-2591.1967.tb01202.x
9. Frank AL. Therapy for the divergent pulpless tooth by continued apical formation. J Am Dent Assoc. 1966;72(1):87-93. https://doi.org/10.14219/jada.archive.1966.0017
10. Torabinejad M, Chivian N. Clinical Applications of Mineral Trioxide Aggregate. J Endod. 1999;25(3):197-205. https://doi.org/10.1016/S0099-2399(99)80142-3
11. Cvek M. Prognosis of luxated non-vital maxillary incisors treated with calcium hydroxide and filled with gutta-percha. A retrospective clinical study. Vol. 8, Dental Traumatology. 1992. p. 45-55. https://doi.org/10.1111/j.1600-9657.1992.tb00228.x
12. Reynolds K, Johnson JD, Cohenca N. Pulp revascularization of necrotic bilateral bicuspids using a modified novel technique to eliminate potential coronal discolouration: A case report. Int Endod J. 2009;42(1):84-92. https://doi.org/10.1111/j.1365-2591.2008.01467.x
13. Banchs F, Trope M. Revascularization of immature permanent teeth with apical periodontitis: New treatment protocol. J Endod. 2004;30(4):196-200. https://doi.org/10.1097/00004770-200404000-00003

14. Günal E, Bezgin T. Rejeneratif Endodonti Klinik Uygulamalarında Dikkat Edilecek Noktalar. AÜ Diş Hek Fak DergÜ Diş Hek Fak Derg. 2020;47((1-3)):179-86.
15. Farah JW, Craig RG. Finite Element Stress Analysis of a Restored Axisymmetric First Molar. J Dent Res. 1974;53(4):859-66. https://doi.org/10.1177/00220345740530041701
16. Belli S, Eraslan O, Eskitaşçıoğlu G. Effect of Different Treatment Options on Biomechanics of Immature Teeth: A Finite Element Stress Analysis Study. J Endod. 2018;44(3):475-9. https://doi.org/10.1016/j.joen.2017.08.037
17. Ronald L. Sakaguchi JMP. Craig's Restorative Dental Materials. 13th ed. St Louis: CV Mosby; 2012. 24-32 p.
18. Magne P. Efficient 3D finite element analysis of dental restorative procedures using micro-CT data. Dent Mater. 2007;23(5):539-48. https://doi.org/10.1016/j.dental.2006.03.013
19. Ichim I, Schmidlin PR, Kieser JA, Swain M V. Mechanical evaluation of cervical glass-ionomer restorations: 3D finite element study. J Dent. 2007;35(1):28-35. https://doi.org/10.1016/j.jdent.2006.04.003
20. Malek S, Darendeliler MA, Rex T, Kharbanda OP, Srivicharnkul P, Swain M, et al. Physical properties of root cementum: Part 2. Effect of different storage methods. Am J Orthod Dentofac Orthop. 2003;124(5):561-70. https://doi.org/10.1016/S0889-5406(03)00398-6
21. Monteiro JM, Chang CT. The elastic moduli of calcium hydroxide. Cem Concr Res. 1995;25(8):1605-9. https://doi.org/10.1016/0008-8846(95)00154-9
22. Eram A, Zuber M, Keni LG, Kalburgi S, Naik R, Bhandary S, et al. Computer Methods and Programs in Biomedicine Finite element analysis of immature teeth filled with MTA, Biodentine and Bioaggregate. Comput Methods Programs Biomed. 2021;190(2020):105356. https://doi.org/10.1016/j.cmpb.2020.105356
23. Ruse ND. Propagation of erroneous data for the modulus of elasticity of periodontal ligament and gutta percha in FEM/FEA papers: A story of broken links. Dent Mater. 2008;24(12):1717-9. https://doi.org/10.1016/j.dental.2008.04.006
24. Sengul F, Gurbuz T, Sengul S. Finite element analysis of different restorative materials in primary teeth restorations. Eur J Paediatr Dent. 2014;15(1):317-22.
25. Adıgüzel Ö, Kaya S, Özer SY, Değer Y, Başaran EG, Yavuz İ. Three-dimensional Finite Element Analysis of Endodontically Treated Tooth Restored with Carbon and Titanium Posts. Int Dent Res. 2011;1(2):55-9. https://doi.org/10.5577/intdentres.2011.vol1.no2.3
26. Anthrayose P, Nawal RR, Yadav S, Talwar S, Yadav S. Effect of revascularisation and apexification procedures on biomechanical behaviour of immature maxillary central incisor teeth: a three-dimensional finite element analysis study. Clin Oral Investig. 2021;25(12):6671-9. https://doi.org/10.1007/s00784-021-03953-1
27. Çetinkaya A. Farklı Tedavi Yöntemleri Uygulanmış Kök Ucu Açık Maksiller Santral Dişlerde Farklı Yönde Uygulanan Kuvvetlerin Oluşturduğu Streslerin Değerlendirilmesi: Sonlu Elemanlar Stres Analizi. Ordu Üniversitesi Diş Hekimliği Fakültesi Endodonti Anabilim Dalı; 2020.
28. Belli S, Eraslan O, Eskitascioglu G. Effect of Root Filling on Stress Distribution in Premolars with Endodontic-Periodontal Lesion: A Finite Elemental Analysis Study. J Endod. 2016;42(1):150-5. https://doi.org/10.1016/j.joen.2015.09.010
29. Özdemir SB, Kahvecioğlu F. Kök ucu açık dişlerde sonlu elemanlar analizi kullanılarak farklı yönlerden gelen travmaların oluşturduğu streslerin değerlendirilmesi. 2020;325:318-25. https://doi.org/10.15311/selcukdentj.685347
30. Ok E, Altunsoy M, Tanriver M, Capar ID, Kalkan A, Gok T. Fracture resistance of simulated immature teeth after apexification with calcium silicate-based materials. Eur J Dent. 2016;10(2):188-92. https://doi.org/10.4103/1305-7456.178301
31. Belli S, Eraslan O, Eskitaşçıoğlu G K V. Monoblocks in root canals: A finite elemental stress analysis study. Int Endod J. 2011;44(9):817-26. https://doi.org/10.1111/j.1365-2591.2011.01885.x
32. Demirel A, Bezgin T, Sarı Ş. Effects of Root Maturation and Thickness Variation in Coronal Mineral Trioxide Aggregate Plugs Under Traumatic Load on Stress Distribution in Regenerative Endodontic Procedures: A 3-dimensional Finite Element Analysis Study. J Endod. 2021;47(3):492-499.e4. https://doi.org/10.1016/j.joen.2020.11.006
33. Bucchi C, Marcé-Nogué J, Galler KM, Widbiller M. Biomechanical performance of an immature maxillary central incisor after revitalization: a finite element analysis. Int Endod J. 2019;52(10):1508-18. https://doi.org/10.1111/iej.13159
34. Bezgin T, Günal E. Devītal genç süreklī dīşlerde endodontīk tedavīler. Ankara; 2018. 1-10 p.
35. Jefferies SR. Bioactive and biomimetic restorative materials: A comprehensive review. part i. J Esthet Restor Dent. 2014;26(1):14-26. https://doi.org/10.1111/jerd.12069
36. Bayram E, Bayram HM. Fracture resistance of immature teeth filled with mineral trioxide aggregate, bioaggregate, and biodentine. Eur J Dent. 2016;10(2):220-4. https://doi.org/10.4103/1305-7456.178310
37. Nagas E, Cehreli ZC, Uyanik O, Vallittu PK, Lassila LVJ. Reinforcing Effect of Glass Fiber-incorporated ProRoot MTA and Biodentine as Intraorifice Barriers. J Endod. 2016;42(11):1673-6. https://doi.org/10.1016/j.joen.2016.08.002
38. Özdemir SB. Kök Ucu Açık Dişlerde Sonlu Elemanlar Analizi Kullanılarak Farklı Yönlerden Gelen Travmaların Oluşturduğu Streslerin Değerlendirilmesi. 2017.