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Influence of Apical Plug Material and Thickness on the Fracture Resistance of Simulated Young Immature Permanent Incisors: An *in vitro* Study

Vatsa Vandana*, Naga Sree Bala, Dwitha Animi Reddy, Rebecca Vaschalya Charlet, Harakabhavi Mutt Niharika, Srinivas Nallanchakrava

Department of Pedodontics, Panineeya Mahavidhyalaya Institute of Dental Sciences and Research Centre, Hyderabad, Telangana, India.

***Corresponding author:**
Vatsa Vandana
Department of Pedodontics, Panineeya Mahavidhyalaya Institute of Dental Sciences and Research Centre, Hyderabad, Telangana, India.
Email: *vandanavatsa08@gmail.com*

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Abstract

Background: Traumatic dental injuries, deep caries, and pulpal pathosis affecting young permanent teeth often interrupt normal root development, resulting in immature teeth. Apexification is a well-established treatment modality for managing non-vital immature teeth, aimed at creating an apical barrier that allows effective obturation of the root canal system. The thickness of the apical plug plays a crucial role in achieving an effective apical seal and influencing fracture resistance.

Aim: To evaluate and compare the fracture resistance of various root end filling materials of different thicknesses in simulated young permanent incisors.

Materials and methods: A total of 56 human permanent maxillary incisors were selected and equally distributed into three experimental groups (each with two subgroups) and two control groups (Groups I and II). The experimental groups were subdivided based on apical plug thickness (3 mm and 6 mm). Access cavities were prepared in all groups except the negative control (Group I). A 3 mm apical plug was placed in Groups IIIA, IVA, and VA. In comparison, a 6 mm apical plug was placed in Groups IIIB, IVB, and VB using MTA, Biodentine, and Dyract compomer, respectively. The positive control group was obturated with calcium hydroxide (Group II) to the whole length other three groups were obturated with GP with AH Plus sealer. All the samples were then subjected to fracture testing under a Universal Testing Machine, and fracture strength was recorded. Data were analysed using one-way analysis of variance with the Tukey post hoc test for multiple comparisons.

Results: The negative control group exhibited the lowest fracture resistance compared to the other groups ($P < 0.0001$). The Biodentine group with a 6mm thickness of apical plug showed the highest fracture resistance.

Conclusion: MTA, Biodentine and Dyract compomer can be used as an apical plug to increase the fracture resistance of immature teeth.

Keywords: Apexification, Apical plug, Biodentine, Dyract compomer, MTA.

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1. Introduction

Most of the traumatic dental injuries occur in the age group of 8 to 9 years, where teeth are still in the developing stages [1]. These injuries may arrest the root development of the affected permanent teeth, resulting in thin dentinal walls, wide-open apexes, and inadequate crown-root ratios, which may present challenges during endodontic treatment [2]. Apexification is considered an effective treatment option for the traumatised non-vital immature teeth [3]. Apexification is defined as "a method to induce a calcified barrier in a root with an open apex or the continued apical development of an incomplete root in teeth with necrotic pulp"[4]. To obtain an adequate apical seal of an open apex, an artificial closure with a calcified barrier is essential.

Calcium hydroxide (CH) is the material of choice for apexification because of its high pH and antimicrobial activity. The major disadvantage reported with this material is the reduction in fracture resistance caused by changes in the organic matrix of dentin following prolonged treatment [2]. To overcome the disadvantage of Calcium Hydroxide, MTA has been recommended as an alternative. The main advantage of MTA is lower solubility and the ability to set in a wet environment. However, it has a few disadvantages, including difficulty in handling, long setting time and reduced fracture resistance of teeth [5].

Newer calcium silicate-based materials have been introduced to compensate for the disadvantages of MTA; one among them is Biodentine, which has good sealing ability, short setting time and biomineralization properties. The compressive strength and elasticity modulus is closer to dentin with superior handling characteristics than that of MTA [5].

Compomer, a material with the mixture of fluoride release property of glass ionomer materials with the strength and esthetics of a light-curing composite. It is a light-curing restorative material for all cavity classes in anterior and posterior teeth and is considered a root-end filling material. This material is popular in restorative dentistry because of its good mechanical, aesthetic qualities and biocompatibility. Dyract restorations continuously release fluoride ions, act on the tooth restoration interface as an acid buffer and effectively support the prevention of approximal caries [6,7]. Dyract Compomer is a polyacid-modified composite when used as a root-end filling material, is reported to be as biocompatible as Biodentine [8].

Although MTA is a gold standard material of choice for Apexification, the drawbacks of MTA, such as lower shelf life and high cost, led to the advent of the use of newer materials. So, the present *in vitro* study aimed to compare the effectiveness of MTA, Biodentine and Dyract Compomer when used as apical filling material in simulated young permanent incisors.

2. Materials and methods

The present *in vitro* study was conducted in the Department of Pedodontics, Panineeya Mahavidhyalaya Institute of Dental Sciences and Research Centre, Dilsukhnagar, Hyderabad, Telangana, India, in collaboration with the Indian Institute of Chemical Technology (IICT), Habsiguda, Hyderabad, Telangana, India. This study was approved by the Institutional Ethics Committee (IEC No: PMVIDS&RC/IEC/PEDO/DN/0342-20).

The sample size was calculated based on the means from a pilot study using G*Power software. The Power of the study (1-β) was set at 0.80 to ensure an 80% chance of detecting a true effect, minimizing false negatives. Alpha (α): Set at 0.05 to minimize Type I errors (false positives), providing a 95% confidence level. A sample size of 7 specimens per group was required to detect significant differences.

A total of 56 human permanent incisors with a single root and no root canal bifurcations were included in the study. Teeth with the presence of carious lesions, external resorption, cracks, fracture lines, anomalies, and endodontically treated were excluded. All the specimens were cleaned, sterilised, and stored in Hank's balanced salt solution (HBSS) until the commencement of the study. All specimens were standardized to a root length of 12 mm using a low-speed diamond disc to simulate immature teeth. The samples were then randomly assigned into groups, with seven specimens in each group (Figure 1).

Figure 1. Slicing the apex

Figure 2. Widening the apex

The specimens were divided into six experimental groups and two control groups. Group I served as the negative control, while Group II served as the positive control. Group III consisted of specimens receiving mineral trioxide aggregate (MTA) as an apical plug and was further subdivided based on plug thickness into Group III A (3 mm) and Group III B (6 mm). Group IV included specimens restored with Biodentine as an apical plug and was similarly subdivided into Group IV A (3 mm) and Group IV B (6 mm). Group V comprised specimens restored with Dyract compomer as an apical plug and was divided into Group V A (3 mm) and Group V B (6 mm).

In the negative control (Group I), canal preparation was done using Peeso reamers (Dentsply Maillefer, Switzerland) of size 1-5 in a retrograde manner from the apical to the coronal direction to simulate immature teeth without access cavity preparation (Figure 2). In the positive control and experimental groups, an access cavity was prepared using a No. 4 round bur and a high-speed handpiece. Pulp was extirpated using barbed broaches, and canals were enlarged with rotary Pro taper files till F1 size. To simulate the dentinal thickness of the immature roots, Peeso reamers of sizes 1-5 were used till each size Peeso reamer could easily pass 1 mm beyond the apex (Figure 3). To approximate the CVEKS 3rd stage of root development, a size 6 Peeso reamer was used 3mm below the CEJ in the coronal third of the canal. All the samples were irrigated with 3 ml of 2.5% sodium hypochlorite solution followed by 3 ml of saline. Canals were dried with paper points to receive an apical plug.

Groups were divided based on the material placed. In Group II (positive control), Calcium hydroxide (Calcicur; Voco, Cuxhaven, Germany) was used as a root canal filling material. In Group III, Mineral Trioxide Aggregate (MTA) (Angelus Solucoes Odontologicas, Londrina, Brazil), Group IV-Biodentine™(BD) (Septodont, Saint-Maur-des-Fosses-Codex, France), Group V Dyract compomer (Dyract® eXtra Dentsply Sirona USA) were placed respectively (Figure 4). These groups were divided into 2 subgroups based on different thicknesses of apical plug, i.e., in subgroup A of 3 mm thickness, and subgroup B of 6 mm thickness. The canals were obturated in warm vertical compaction technique using Gutta-percha with AH Plus sealer (Dentsply DeTrey, Konstanz, Germany). Access cavity was restored using composite (Clear- fil Majesty Esthetic; Kuraray, Tokyo, Japan).

Periodontal ligament membrane (PDL) simulation of the teeth was done by immersing the sample in a 0.2-0.3 mm thickness of wax, 2mm below the cemto-enamel junction (CEJ), so that wax was coated along the root surface. The samples were embedded at an angle of 45º to the surface in a self-cured acrylic (DPI-Dental Products of India, Mumbai, India) resin block. After polymerization, teeth were removed from resin blocks, and the dewaxing of the root surface was done using warm water. These resin blocks were filled with polyvinyl siloxane-based impression material (Zermack, Italy), and teeth were inserted again into resin blocks so that a gap of 2mm is maintained between the acrylic and facial or lingual CEJ. This was done to simulate the physiological spacing found between the bone crest and CEJ, and also to expose the portion of the tooth that is likely to fracture when horizontal forces are placed on the crown. The entire samples were tested for fracture resistance using a Universal testing machine (Shimadzu corporation, Japan) at a crosshead speed of 1mm/min until fracture. The peak load to fracture was recorded in Newtons.

Figure 3. Access preparation

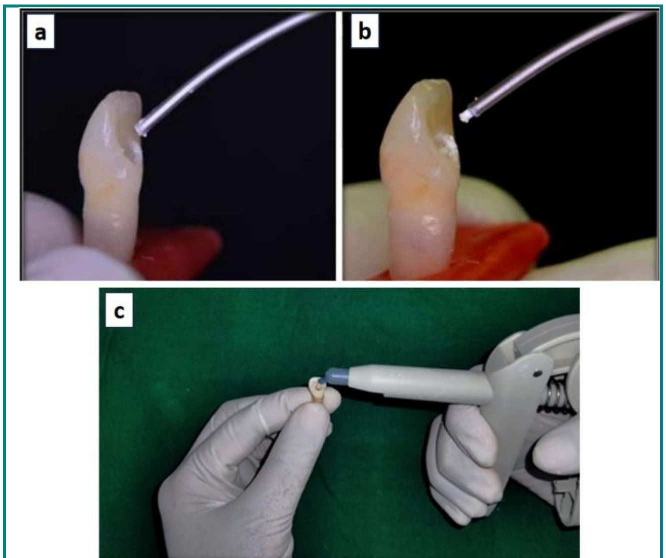

Figure 4. Placement of material, a. MTA, b. Biodentine, and c. Dyract Compomer

After completing the fracture test, the data were subjected to statistical analysis. The SPSS v 25.0 (IBM, USA) software was used for statistical analysis. p-value < 0.05 is considered statistically significant. Tukey's Post hoc analysis is used for multiple comparisons of different groups' mean differences in fracture resistance. The distribution of the data was assessed for normality using the Kolmogorov-Smirnov (KS) test, and since the data followed a normal distribution, parametric tests were conducted.

3. Results

The negative control group showed the lowest fracture resistance compared with the other groups (P < 0.0001). The 6-mm apical plug group of Biodentine (Group IV B) showed the highest fracture resistance, as presented in Table 1. For the experimental groups, there was a significant difference between groups of 3mm thickness vs 6mm thickness (Table 2). When the mean difference of fracture resistance in group I was compared with other groups, a statistically significant difference (P<0.001) was noted. Comparisons between group II with Group VA, group IIIA with groups IVA and VB, Group IIIB with group VB, and group IVA with group VB showed statistically insignificant differences (p > 0.05). The remaining groups showed statistically significant values (p < 0.05) (Table 3). Comparison of fracture resistance at the same thickness of 3mm of groups (IIIA, IVA, and VA) showed statistical significance. The same results were seen in groups IIIB, IVB and VB at 6mm thickness (Table 4).

Table 1. Comparison of fracture resistance (One-Way ANOVA).

Groups	Minimum	Maximum	Mean	SD	p value
Gr I	124	241	163.80	41.72	0.001*
Gr II	167	262	219.13	33.88	
Gr IIIA	293	352	319.69	22.92	
Gr IIIB	330	430	368.36	32.66	
Gr IVA	295	393	334.53	35.94	
Gr IVB	531	608	564.19	33.63	
Gr VA	156	381	259.13	72.78	
Gr VB	209	451	326.49	79.14	

SD: Standard deviation; *Significant difference.

Table 2. Comparison of the fracture resistance between the experimental groups at different thicknesses (Student's t-test).

Groups	3mm thickness		6mm thickness		t-value	p-value
	Mean	SD	Mean	SD		
Gr IIIA vs Gr III B	319.68	22.92	368.35	32.66	-3.23	0.00362*
Gr IVA vs Gr IVB	334.53	35.94	564.18	33.63	-12.35	0.00001*
Gr VA vs Gr VB	244.82	72.78	355.08	79.14	-4.00	0.00087*

SD: Standard deviation; *Significant difference.

Table 3. Multiple comparisons of fracture resistance of various groups using Tukey's Post hoc analysis.

Groups		Mean difference	SD	p-value
Group I	Group II	61.27	47.17	0.008*
	Group IIIA	161.83	89.32	0.00001*
	Group IIIB	210.50	114.48	0.00001*
	Group IVA	176.67	98.40	0.00001*
	Group IVB	406.33	213.67	0.00001*
	Group VA	86.95	62.88	0.003861*
	Group VB	197.23	111.25	0.00001*
Group II	Group IIIA	100.55	59.11	0.000029*
	Group IIIB	149.23	83.77	0.00001*
	Group IVA	115.40	68.64	0.00004*
	Group IVB	345.05	181.95	0.00001*
	Group VA	25.68	44.05	0.293137
	Group VB	135.95	82.02	0.00008*
Group IIIA	Group IIIB	48.67	37.05	0.00725*
	Group IVA	14.84	29.96	0.375039
	Group IVB	244.5	129.84	0.00001*
	Group VA	74.87	54.63	0.004355*
	Group VB	35.4	42.43	0.122104
Group IIIB	Group IVA	33.83	37.36	0.090143*
	Group IVB	195.83	106.48	0.00001*
	Group VA	123.54	76.38	0.000175*
	Group VB	13.27	41.95	0.575031
Group IVA	Group IVB	229.65	123.76	0.00001*
	Group VA	89.71	123.76	0.00001*
	Group VB	20.55	43.93	0.403027
Group IVB	Group VA	319.37	170.93	0.00001*
	Group VB	209.1	116.25	0.00001*
Group VA	Group VB	110.27	75.68	0.0017*

SD: Standard deviation; *Significant difference.

Table 4. Inter-group comparison of Fracture resistance at 3mm and 6mm thickness

Thickness	Group IIIA	Group IVA	Group VA	p-Value
3mm	Mean ± SD	Mean ± SD	Mean ± SD	
	319.68 ± 22.92	334.53 ± 35.94	244.81 ± 72.79	0.000822 *
	Group IIIB	**Group IVB**	**Group VB**	**p-Value**
6mm	Mean ± SD	Mean ± SD	Mean ± SD	
	368.35 ± 32.65	564.18 ± 33.62	355.08 ± 79.14	<0.00001*

SD: Standard deviation; *Significant difference.

4. Discussion

This study aimed to evaluate the fracture resistance of immature teeth when different materials at various thicknesses are used as apical plugs. Traumatic dental injuries are common in young individuals, with incisors, especially central incisors, being frequently involved. This was reported by Ravn *et al*. [9], who found a 70% prevalence of dental injuries in the age group between 8 and 9 years. During this period, dental caries and trauma pose the most significant challenges in preserving tooth integrity as it matures [10,11]. The possible treatment approach for such a condition is Apexification.

A variety of materials were proposed for the induction of apical barrier formation, and calcium hydroxide has gained the widest acceptance due to its antibacterial capability and high alkalinity [12]. CH was used for many years for apical closure, but it has many disadvantages, including unpredictable time required to form an apical barrier, the need for multiple visits, patient compliance, re-infection because of loss of the temporary restoration, and predisposition of the fracture [13]. The present study also showed that CH had adversely affected the fracture resistance of the root when compared with the 3-mm MTA as well as the 6-mm MTA. The decreased root strength observed in the CH treated root canals could be associated with the weakened dentin, which might occur as a result of denaturation and hydrolysis taking place in the organic matrix [14].

The introduction of MTA in 1993 provided a successful alternative with advantages including the establishment of an instant apical barrier, setting ability in a wet environment, promising sealing ability, improving patient compliance, ease of handling, and possibly increased fracture resistance of immature teeth. MTA acts like a scaffold for the formation of hard tissue and a better biological seal as compared to CH, as stated by Witherspoon and Ham [14]. In addition, MTA almost doubles the secretion of Vascular Endothelial Growth Factor in dentine pulpal stem cells (DPSCs), which helps in dentine repair/mineralization [15]. A. Pinar Erdem *et al.* (2008) [16] proved that MTA is a very effective option for apexification with the advantage of reduced treatment time, good sealing ability and high biocompatibility, by investigating the clinical and radiographic success rate of using MTA in open apices at 6 months, 1-year and 2-year follow-up periods. Similar results were also seen by Bonte E *et al.* (2014) when MTA and CH were used as materials for inducing root apex closure in immature necrotic permanent incisors, and the MTA group displayed better results in terms of apical closure. The main drawbacks of MTA include difficult handling characteristics, long setting time, high material cost, and the difficulty of its removal after its setting [17].

Biodentine is a bioactive calcium silicate-based cement which has been introduced into the field of dentistry as a ‘dentin substitute’. [18]. Elnaghy AM *et al*. (2016) revealed that Biodentine-filled teeth have a similar fracture resistance with no statistical difference after 12 months when compared with WMTA. [19]. This finding suggests that Biodentine could be considered as an apical barrier in an immature permanent tooth, and contrary to the present study, both MTA and BD showed a statistically significant difference.

Dyract Compomer (Dentsply USA), a polyacid-modified composite resin introduced in 1994, shows the benefits of both Glass ionomer and Composite resins with good mechanical properties, biocompatibility, tooth adhesion, good retention, and marginal seal, fluoride release, and excellent aesthetics, which is available in compules [6]. Fuat Ahmetoglu et al. (2014) [20] conducted a study to compare the sealing ability of different glass ionomer cements (GIC) as root-end filling (RF) materials, in which Dyract Compomer provided more successful sealing than Ketac Molar.

Materials at different thicknesses have been chosen for the following reasons. First, placement through an access cavity with minimal resistance at the apex may make the thickness difficult to control. Second, the amount placed as a plug will determine the maximum depth of the gutta-percha that could be used to reinforce the tooth. The greater the plug thickness, the less root length available for bonding, which could impact the strength attainable on a short, immature root [6].
The apical plug should provide a hermetic apical seal. Various studies have reported that a 3 to 5 mm thickness of MTA provided an effective apical seal. [21,22]. A study done by Cicek *et al*. compared different thicknesses of MTA used as apical plug and its effect on fracture resistance of immature teeth and confirmed that a minimum 3mm apical plug thickness is required and the use of an elastic material such as gutta-percha could be recommended in the upper part of the canal, instead of a non - elastic material such as MTA to prevent any adverse effect on fracture resistance of teeth [2].

Bayram E *et al*. (2016) [23] studied the fracture resistance of teeth with immature apices treated with coronal placement of MTA, Bioaggregate (BA), and Biodentine (BD) in which the MTA group showed the highest fracture resistance, followed by BA and Biodentine, which is contrary to the present study. An investigation was done by Sarraf P *et al*. (2019) [24] on the fracture resistance of immature bovine roots filled with root-end filling materials like ProRoot MTA, CEM Cement, and BD and concluded that BD and ProRoot MTA groups had the greatest fracture resistance. On comparison, the fracture resistance of simulated immature teeth after using different thicknesses of

(MTA) and BD apical plugs of 3mm,6mm, and full canal length by Mohite P *et al.* (2022) [25] and concluded that the 6-mm apical plug subgroup of BD showed the highest fracture resistance, which is similar to the present study. Bill D. Greer *et al*. conducted a study to evaluate the apical sealing ability of two compomers (Dyract and Geristore), IRM, and Super-EBA and stated that the new compomers Dyract and Geristore are equal or superior to IRM and equivalent to Super-EBA in their ability to reduce apical leakage when used as retrofilling materials [7]. The apical plug should provide a hermetic apical seal. The present study results showed that a 6mm apical plug followed by obturation of the root canal with BD showed higher fracture resistance. In contrast to the finding, a difference was found between a 3 and 6 mm MTA, BD and Compomer apical plugs, and showed different results.

Therefore, MTA, Biodentine, and Compomer may be safely used for performing an apical barrier between 3- and 6-mm thick in immature teeth. Because the use of AH 26 plus gutta-percha increases the fracture resistance of instrumented root canals, the use of an elastic material such as gutta-percha could be recommended in the upper part of the canal, instead of an inelastic material. An apical plug could be placed into the root canal up to 6 mm thick, if required, during the single-visit treatment of immature teeth without adversely affecting the resistance of tooth structures. *In vivo* studies should be conducted as a simulation of teeth may not give correct results. The root thickness cannot be standardized beacause of samples collected are from different age groups.

5. Conclusion

Within the limitations of the study, the research suggests that Biodentine as a 6 mm apical plug has higher fracture resistance when compared to other experimental groups. Considering the shorter setting time and improved handling characteristics, Biodentine can be preferred over MTA as an apical plug.

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References

1. Shah N, Logani A, Bhaskar U, Aggarwal V. Efficacy of revascularization to induce apexification/apexogenesis in infected, nonvital, immature teeth: a pilot clinical study. J Endod. 2008;34(8):919-25. https://doi.org/10.1016/j.joen.2008.05.001
2. Çiçek E, Yılmaz N, Koçak MM, Sağlam BC, Koçak S, Bilgin B. Effect of Mineral Trioxide Aggregate Apical Plug Thickness on Fracture Resistance of Immature Teeth. J Endod. 2017;43(10):1697-1700. https://doi.org/10.1016/j.joen.2017.05.007
3. Akbulut MB, Arpaci PU, Eldeniz AU. Effects of four novel root-end filling materials on the viability of periodontal ligament fibroblasts. Restor Dent Endod. 2018 25;43(3):e24:1-12. https://doi.org/10.5395/rde.2018.43.e24
4. American Association of Endodontists. Glossary of endodontic terms. Chicago: American Association of Endodontists; 2020, 10th Edition. Available from: https://www.aae.org/specialty/clinical-resources/glossary-endodontic-terms/
5. 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
6. Jayasree S. Compomer–Dyract: A comparison of its bond strength and microleakage with composite resin and glass ionomer–An in vitro study. IOSR J Dent Med Sci. 2017;16:32-42.
7. Greer BD, West LA, Liewehr FR, Pashley DH. Sealing ability of Dyract, Geristore, IRM, and super-EBA as root-end filling materials. J Endod. 2001 ;27(7):441-3. https://doi.org/10.1097/00004770-200107000-00001
8. Silujjai J, Linsuwanont P. Treatment Outcomes of Apexification or Revascularization in Nonvital Immature Permanent Teeth: A Retrospective Study. J Endod. 2017;43(2):238-45. https://doi.org/10.1016/j.joen.2016.10.030
9. Ravn JJ. Dental injuries in Copenhagen schoolchildren, school years 1967-1972. Community Dent Oral Epidemiol. 1974;2(5):231-45. https://doi.org/10.1111/j.1600-0528.1974.tb01657.x-i1
10. Grayli E, Dashtban A, Shadan L, Behnampour N, Afshari E. Effect of MTA versus CEM apical plugs on fracture resistance of endodontically treated simulated immature teeth restored with cast metal posts: an in-vitro study. BMC Oral Health. 2021;21(1):280. https://doi.org/10.1186/s12903-021-01641-w
11. Hemalatha H, Sandeep M, Kulkarni S, Yakub SS. Evaluation of fracture resistance in simulated immature teeth using Resilon and Ribbond as root reinforcements--an in vitro study. Dent Traumatol. 2009;25(4):433-8. https://doi.org/10.1111/j.1600-9657.2009.00804.x
12. 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
13. Andreasen JO, Farik B, Munksgaard EC. Long-term calcium hydroxide as a root canal dressing may increase risk of root fracture. Dent Traumatol. 2002;18(3):134-7. https://doi.org/10.1034/j.1600-9657.2002.00097.x
14. Witherspoon DE, Ham K. One-visit apexification: technique for inducing root-end barrier formation in apical closures. Pract Proced Aesthet Dent. 2001;13(6):455-60.
15. Patel E, Pradeep P, Kumar P, Choonara YE, Pillay V. Oroactive dental biomaterials and their use in endodontic therapy. J Biomed Mater Res B Appl Biomater. 2020;108(1):201-12. https://doi.org/10.1002/jbm.b.34379
16. Erdem AP, Sepet E. Mineral trioxide aggregate for obturation of maxillary central incisors with necrotic pulp and open apices. Dent Traumatol. 2008;24(5):e38-41. https://doi.org/10.1111/j.1600-9657.2008.00636.x
17. Bonte E, Beslot A, Boukpessi T, Lasfargues JJ. MTA versus Ca(OH)2 in apexification of non-vital immature permanent teeth: a randomized clinical trial comparison. Clin Oral Investig. 2015;19(6):1381-8. https://doi.org/10.1007/s00784-014-1348-5

18. Raghavendra SS, Jadhav GR, Gathani KM, Kotadia P. Bioceramics in endodontics - a review. J Istanb Univ Fac Dent. 2017;51(3 Suppl 1):S128-S137. https://doi.org/10.17096/jiufd.63659
19. Elnaghy AM, Elsaka SE. Fracture resistance of simulated immature teeth filled with Biodentine and white mineral trioxide aggregate - an in vitro study. Dent Traumatol. 2016;32(2):116-20. https://doi.org/10.1111/edt.12224
20. Ahmetoglu F, Topçu KM, Orucoglu H. Comparison of the sealing ability of different glass ionomer cements as root-end filling materials. J Res Dent. 2014 ;2:27-31. https://doi.org/10.4103/2321-4619.129014
21. Lolayekar N, Bhat SS, Hegde S. Sealing ability of ProRoot MTA and MTA-Angelus simulating a one-step apical barrier technique-an in vitro study. J Clin Pediatr Dent 2009;33:305–10. https://doi.org/10.17796/jcpd.33.4.gp472416163h7818
22. Koçak MM, Koçak S, Aktuna S, Görücü J, Yaman SD. Sealing ability of retrofilling materials following various root-end cavity preparation techniques. Laser Med Sci. 2011;26(4):427-31. https://doi.org/10.1007/s10103-010-0789-6
23. Bayram E, Bayram HM. Fracture resistance of immature teeth filled with mineral trioxide aggregate, bioaggregate, and biodentine. Eur J Dent. 2016;10(2):220-24. https://doi.org/10.4103/1305-7456.178310
24. Sarraf P, Nekoofar MH, Sheykhrezae MS, Dummer PMH. Fracture Resistance of Immature Incisors Following Root Filling with Various Bioactive Endodontic Cements Using an Experimental Bovine Tooth Model. Eur J Dent. 2019 ;1(2):156-160. https://doi.org/10.1055/s-0039-1695654
25. Mohite P, Ramteke AD, Gupta R, Patil S, Gupta D. Comparative evaluation of mineral trioxide aggregate and biodentine apical plug thickness on fracture resistance of immature teeth: An In vitro study. Ann Afr Med 2022;21:198-203. https://doi.org/10.4103/aam.aam_97_20