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A Weibull analysis of the reinforcing effect of intra-radicular filling materials on the mineral trioxide aggregate apical barrier in simulated immature mandibular premolars

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ABSTRACT

Introduction: After pulp necrosis, incomplete root development necessitates the apexification of mineral trioxide aggregate (MTA). Despite its effectiveness, this treatment does not thicken the roots, therefore, more reinforcement is required. The purpose of this study was to assess the fracture resistance of artificially created immature mandibular premolars strengthened with different materials and apexified with MTA utilizing Weibull analysis.

Methods: 90 human mandibular first premolars were created to mimic juvenile teeth. Following MTA apexification, teeth were split into six groups: gutta-percha (GP) with AH Plus, GP with Bioceramic sealer, core, and fiber post/core; negative control (intact teeth); and positive control (untreated apexified teeth). The teeth were subjected to fracture testing, periodontal ligament simulation, and thermocycling.

Results: Negative and positive controls exhibited the highest and lowest fracture resistance, respectively. Core and fiber post/core (hazard ratios of 4.79 and 6.23, respectively)outperformed GP with AH Plus and GP with Bioceramic sealer (hazard ratios of 14.23 and 17.22 respectively). The coronal third was where the majority of fractures happened.

Conclusions: Compared to traditional root filling materials (GP/AH Plus and GP/Bioceramic sealer), intraradicular reinforcement materials (fiber post/core and core) offered MTA-apexified roots more support.

Keywords: Apexification, Fracture resistance, Intraradicular reinforcement, Mineral trioxide aggregate, Weibull analysis

INTRODUCTION

Teeth with thin root canal walls and wide-open apices can be the result of dental pulp damage during root development, which can also cause pulpal necrosis and inadequate root formation (1).Apexification of mineral trioxide aggregate (MTA) offers superior sealing, low cytotoxicity and antibacterial properties (2),but it doesn't lengthen or thicken the roots, making teeth more brittle (3) and requiring reinforcement to fortify the root.

Gutta-percha (GP)/sealer, cement based on calcium silicate, resin-based core build-up materials, and prefabricated fiber post are among the intraradicular reinforcing materials that have been tested in vitro under simulated conditions (4–8). In comparison to GP/sealer and nonreinforced teeth with MTA apexification (6, 10–14), prefabricated fiber posts have demonstrated superior fracture resistance (6, 8–13)

Bioceramic root canal sealers based on calcium silicate have shown benefits including bioactivity to encourage the development of hydroxyapatite (16) and biocompatibility with periapical tissues (15).Additionally, they offer dentin bonding from sealer to root, this could make the root stronger and lower the chance of vertical root fractures (17, 18). It is unknown, therefore, how the bioceramic sealer affects the juvenile teeth's susceptibility to shatter during MTA apexification. Furthermore, the majority of research has been on anterior teeth (4, 5), with mandibular premolars (6, 8, 13) receiving less attention. Reinforcement techniques may be impacted by premolar traits such as dens evaginatus, oval-shaped canals, and varying occlusal loading orientations (19)

When examining the frequency of failure, Weibull analysis is helpful, particularly when sample numbers are small. It offers information on the likelihood of failure at various stress levels.

Thus, the purpose of this work was to use Weibull analysis to examine the fracture resistance of simulated immature mandibular premolars that were apexified with MTA and strengthened with various intraradicular materials. There should be no discernible variations in the fracture resistance offered by the different intraradicular filler materials, according to the null hypothesis.

MATERIALS AND METHODS

Ethics approval: The study proposal was accepted after being blinded for evaluation.

Tooth Selection

Sample size calculation: Using the Ftest (G*Power 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) with an effect size of 0.52, 90% power, and 5% significant level, the sample size was determined to be at least 15 per group.

Sample collection : A 0.12% thymol solution was used to store 90 single-root permanent mandibular first premolars with mature roots (extracted for orthodontic purposes); the teeth measured 7–9 mm in crown height and 12–14 mm in root length. Teeth that had fractures, cracks, resorption, or cavities were not included. Debris and calculus were eliminated by ultrasonic scaling (P5; Acteon, Norwich, UK), and radiographs verified that there was no canal calcification, internal root resorption, or additional canals. Root canal morphology was categorized as either "oval" (width ratio >1 but <2) or "long oval" (width ratio ≥2 but <4) based on width ratio (21). Based on the dentin thickness ratio (buccolingual/mesiodistal), teeth were divided into two groups. The maximum to minimum width ratio was set at 1.5. ANOVA, chi-square, and Kruskal-Wallis tests guaranteed randomization and proportional distribution.

Six sets of teeth were randomly assigned: negative control (teeth in their original state), four experimental groups and a positive control. After coronal access, the experimental and positive control groups' root lengths were standardized at 19 mm.

Preparation of simulated immature teeth

Root canal preparation :K-files were used to gradually extend the canals in the experimental groups. Peeso reamers (#1–3) (Dentsply Sirona) and (#15–50) (Dentsply Sirona, Charlotte, NC, USA) via the coronal access. Using Peeso reamers (#1–4) in the opposite direction through the apex, the apical third preparation was carried out. During preparation, the irrigation routine used 2.5% NaOCl (M-Dent, Bangkok, Thailand). To remove the smear layer, a final rinse was performed using 3 mL of 17% EDTA (M-Dent) and 5 mL of 2.5% NaOCl. Radiographs were used to measure the residual dentin thickness in the buccolingual and mesiodistal dimensions at 11, 8, and 4 mm from the apex; no discernible variations between the groups were found (Table 1).

MTA apical plug :At 100% humidity, a 4-mm-thick MTA apical plug was made and let to set for 24 hours. Radiographs in the buccolingual and mesiodistal views verified the plug's thickness and density. The MTA was refilled after being cleaned with regular saline if any voids were found.

Intraradicular filling materials : The experimental and positive control groups (Groups 1–4) had the remaining root canal segments prepared as follows:

Positive control : The cementoenamel junction (CEJ) was reached by inserting a cotton pellet into the root canal.

Group 1: AH Plus and GP
Warm vertical compaction was used to introduce thermoplasticized GP (Dentsply Sirona) in 2-mm increments up to the CEJ afterthe canal walls had been coated with AH Plus using a K-file.

Group 2: Bioceramic sealer and GP
Using a syringe tip and lentulo spiral up to the CEJ, bioceramic sealer (iRoot SP; Innovative Bioceramix, Vancouver, Canada) was administered. The sealer was applied to the standardized main cone (size 110/taper.02), which was then inserted and compressed all the way to the CEJ.

Group 3: Core composite
The composite core (MultiCore Flow; IvoclarVivadan) was positioned up to 2 mm below the cavity margin and allowed to cure for 40 seconds following 15 seconds of etching with 37% phosphoric acid (3M Scotchbond Etchant; 3M-ESPE, St. Paul, MN, USA) and 10 seconds of application of Excite F DSC adhesive (Excite F DSC; IvoclarVivadan, Schaan, Liechtenstein).

Group 4: Composite core and fiber post
As in Group 3, the canal was etched and bonded. The post was treated with a silane coupling agent (Monobond N; IvoclarVivadent). The core material was inserted into the canal, and then a fiber post (D.T. Light-Postsize 2; RTD Dental, Saint-Egrève, France) was placed inside and polymerized. Two millimeters below the cavity margin, the fiber post and core were trimmed back.

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70% ethanol was used to sanitize the coronal access. The unbonded material (IRM; Dentsply Sirona) was used as the positive control. The coronal access for groups GP/AH Plus and GP/Bioceramic sealer was etched using 37% phosphoric acid, bonded using Adper Single Bond 2 Adhesive (3M ESPE), and restored using 2-mm resin composite (3M™ Filtek Z250; 3M ESPE) and 4-mm bulk fill flowable composite (SDR flow+ Bulk Fill Flowable; Dentsply Sirona). Only a 2-mm layer of resin composite (3M™ Filtek Z250; 3M ESPE) was applied to groups core and fiber post/core following the placement of the corresponding core materials (Fig. 1).

ImageJ (National Institutes of Health, Bethesda, MA, USA) was used to radiographically evaluate the voids in the root canal filling. Specimens that had voids larger than 5% of the entire material area were swapped out.

Before testing, the specimens were stored for seven days at 37 °C (100% humidity) to allow the sealer to set.

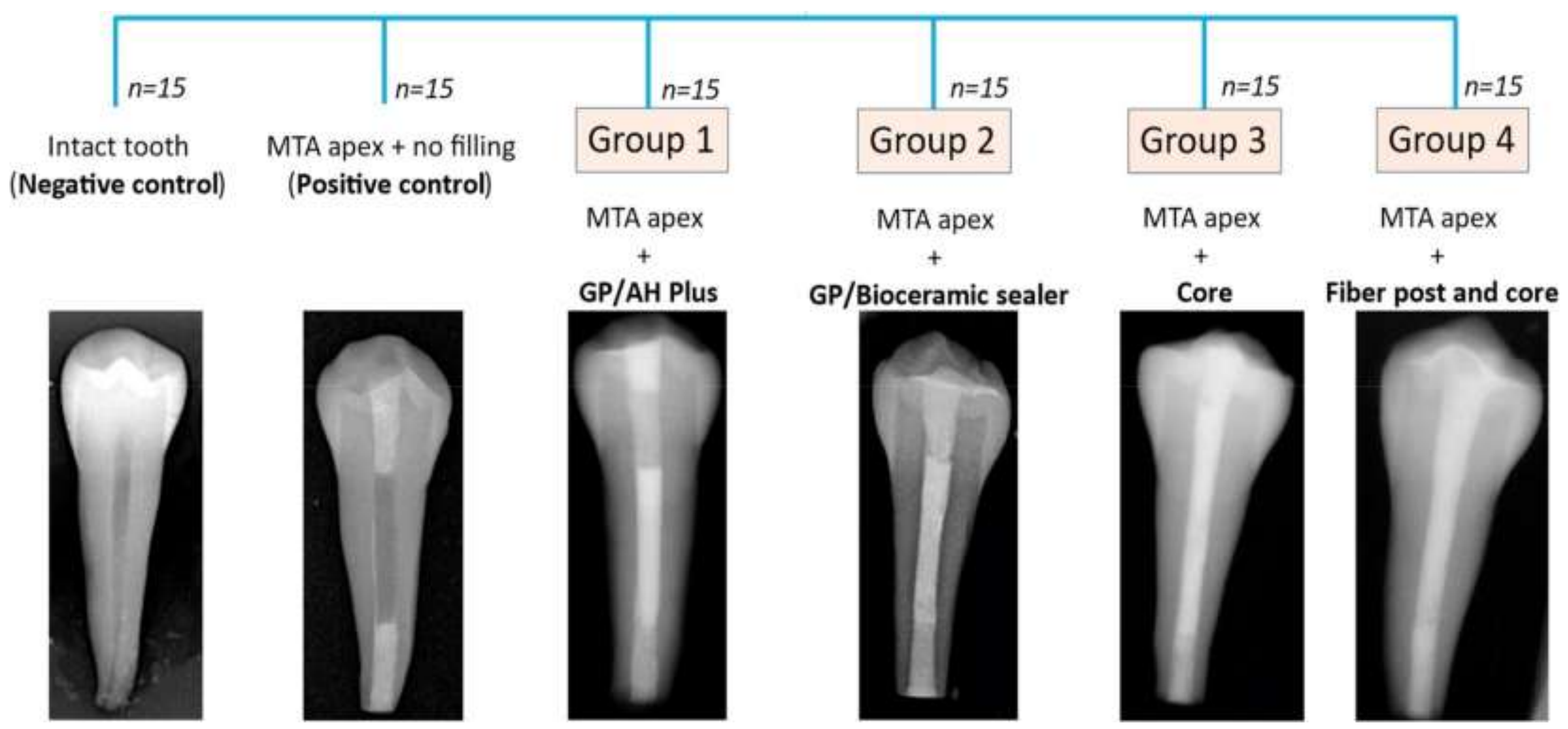

Figure 1. Radiographic examples of typical teeth from each group.

Thermocycling and Periodontal ligament simulation

The specimens were thermocyclically cycled 500 times in distilled water at 5 and 55 °C (dwell time: 30 s; transfer time: 5 s) using a TC400 (King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand) [4]. A small coating of wax and silicone-based impression material were applied to resemble the periodontal ligament. About 2 mm below the CEJ, the root was set in a cylindrical PVC tube and sealed with self-cured acrylic resin (Formatray; Meyydent, Nakhon Ratchasima, Thailand).

Fracture testing by static loading

Using a universal testing machine (Instron 5566; Instron Ltd., Buckinghamshire, England), a compressive load was applied at 45° to the tooth's long axis with a stainless-steel cylindrical tip (diameter, 2 mm) at a cross-head speed of 1 mm/min until fracture. Newtons (N) were used to record the fracture load (Fig. 2).

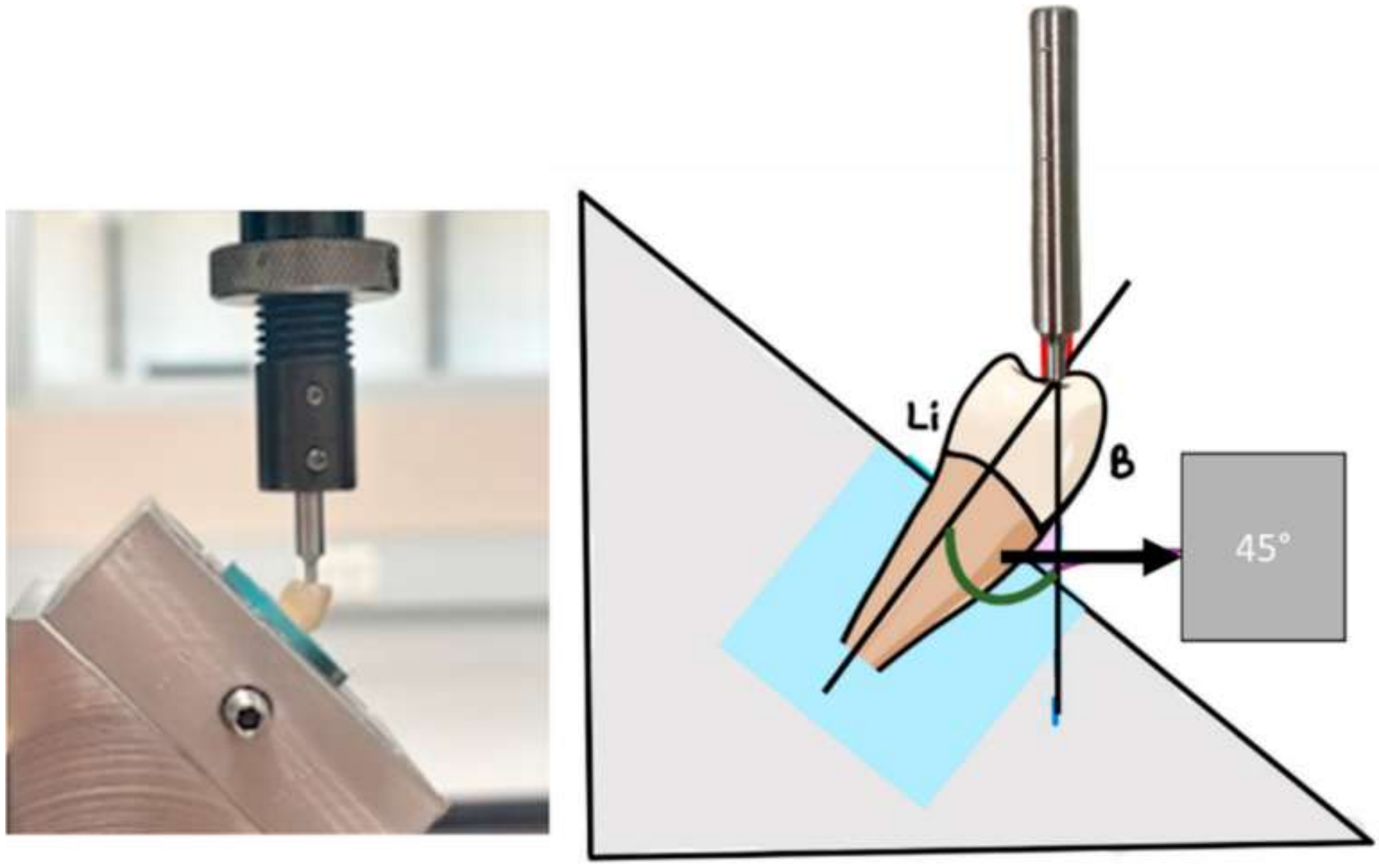

Figure 2. Compression load applied to tooth by using an Instron testing machine to the long axis of the tooth from occlusal with a stainless-steel cylindrical tip (2-mm diameter) at a cross-head speed of 1 mm/min until fracture.

Fracture pattern

Two groups were identified from the distribution of fracture patterns: (1) oblique patterns, which extended diagonally toward the CEJ, and (2) horizontal patterns, which extended parallel to the CEJ in a straight line from right to left. Two groups of fracture locations were identified: (1) coronal, where every fracture was found in the root's coronal third, and (2) middle, where some fracture components were found in the middle third.

Statistical analysis

A thorough assessment of failure probability, survival probability prediction, and systematic comparison among experimental groups were made possible by Weibull analysis using STATA version 17 (StataCorp., College Station, TX, USA). Exponential graphs were used to display the fracture load for every experimental group. At any level, the likelihood of survival and the variation in the load to fracture were predicted. The locations and patterns of fractures in each group were ascertained using descriptive analysis. At $P < 0.05$, statistical significance was established.

RESULTS

The majority of the root canals had a uniform oval shape (100%), and they were oval (73.3%) and lengthy (26.7%). Following preparation, there was no discernible difference in dentin thickness measures (Table 1).

GROUPS							
	(Negative)	(Positive)	1 (GP/AH Plus)	2 (GP/Bioceramic)	3 (Core)	4 (Post/Core)	P-value
Pre-op							
Root thickness (mm)	1.58±0.24	1.62±0.30	1.55±0.19	1.57±0.17	1.58±0.18	1.60±0.18	0.675 (One-way ANOVA)
Dentin thickness (mm)	1.52±0.32	1.49±0.34	1.41±0.23	1.44±0.27	1.5±0.25	1.53±0.38	0.642 (One-way ANOVA)
Root canal width (mm)	1.88±0.68	1.84±0.61	1.91±0.70	2.04±0.81	1.95±0.65	1.93±0.99	0.883 (Kruskal-Wallis)
Root canal morphology	Oval (100%)	Oval (100%)	Oval (100%)	Oval (100%)	Oval (100%)	Oval (100%)	N/A
Root canal shape	Oval (73.3%) Long oval(26.7%)	Oval (73.3%) Long oval (26.7%)	Oval (73.3%) Long oval (26.7%)	Oval (73.3%) Long oval (26.7%)	Oval (73.3%) Long oval (26.7%)	Oval (73.3%) Long oval (26.7%)	1.000(Chi-Square)
Dentin thickness (ratio)	<1.5 (60%) ≥1.5 (40%)	<1.5 (60%) ≥1.5 (40%)	<1.5 (60%) ≥1.5 (40%)	<1.5 (60%) ≥1.5 (40%)	<1.5 (46.7%) ≥1.5 (53.3%)	<1.5 (46.7%) ≥1.5 (53.3%)	0.952(Chi-Square)
Post-op							
Level from apex mm)	Surface						
4	B	1.89±0.27	2.00±0.35	1.73±0.25	1.77±0.26	1.80±0.29	0.206 (Kruskal Wallis)
4	Li	2.29±0.44	2.22±0.37	2.19±0.45	2.23±0.43	2.11±0.29	0.810 (One-way ANOVA)
4	M	1.11±0.29	1.09±0.19	1.11±0.18	1.20±0.43	1.04±0.17	0.341 (One-way ANOVA)
4	D	0.99±0.22	1.14±0.16	1.11±0.17	1.14±0.27	1.03±0.17	0.77 (Kruskal Wallis)

8	B	2.33±0.29	2.23±0.30	2.10±0.24	2.22±0.34	2.11±0.25	0.163 (One-way ANOVA)
8	Li	2.65±0.38	2.49±0.31	2.41±0.40	2.37±0.29	2.46±0.34	0.383 (Kruskal Wallis)
8	M	1.63±0.24	1.51±0.20	1.47±0.23	1.43±0.25	1.49±0.23	0.260 (Kruskal Wallis)
8	D	1.55±0.24	1.71±0.33	1.51±0.18	1.56±0.23	1.45±0.23	0.560 (One-way ANOVA)
11	B	2.43±0.41	2.41±0.26	2.26±0.26	2.32±0.33	2.43±0.30	0.462 (Kruskal Wallis)
11	Li	2.46±0.44	2.35±0.28	2.18±0.37	2.15±0.23	2.27±0.17	0.690 (Kruskal Wallis)
11	M	1.87±0.32	1.81±0.21	1.80±0.19	1.67±0.18	1.89±0.21	0.790 (One-way ANOVA)
11	D	1.99±0.17	2.03±0.25	1.92±0.16	1.98±0.28	1.90±0.28	0.432 (Kruskal Wallis)

Fracture resistance was highest in the negative control group and lowest in the positive control group. With no statistically significant difference from GP/AH Plus, the experimental groups' fracture resistance was lowest for GP/Bioceramic sealer. When compared to fiber post/core, core showed the maximum fracture resistance with no statistically significant difference (Table 2).

Group	**Mean (N)**	**Standard deviation**	**Minimum**	**Maximum**	**HR (95% CI)**	**P-Value**
Negative control	1193.49	195.96	977.41	1724.9	1	Ref
Positive control	473.65	104.02	331.48	663.58	301.98 (98.88, 922.22)	<0.001
GP/AH Plus (Group 1)	838.15^{A}	122.69	628.4	1009.2	17.22^{A}(7.32,40.49)	<0.001
GP/Bioceramic(Group 2)	811.73^{A}	113.53	613.67	941.94	14.23^{A}(6.12,33.07)	<0.001
Core (Group 3)	940.75^{B}	160.68	720.13	1263.13	4.79^{B}(2.24,10.26)	<0.001
Post/Core (Group 4)	937.80^{B}	102.32	802.26	1200.7	6.23^{B}(2.28,13.72)	<0.001

Table 2. Mean load to fracture (Newtons), standard deviation, minimum and maximum, hazard ratio, and 95% confidence intervals of all groups tested and results of pairwise comparisons of marginal linear predictions. The statistical results are calculated using Weibull regression analysis. The different uppercase letters represent significant differences in load to fracture. The probability of failure in the loading force range of 676–918 N corresponds to the maximum normal occlusal force in females and males (Karataban P. et al., 2022)

The experimental groups' susceptibilities to fractures varied (Table 2). Comparable hazard ratios of 17.22 and 14.23 were displayed by GP/AH Plus and GP/Bioceramic, respectively (P = 0.602). There was no discernible difference between the two reinforcement groups' decreased hazard ratios (core, 4.79; fiber post/core, 6.23) (P = 0.474). The coronal portion of the root was where the oblique fracture pattern was most common (Table 3).

Fracture location				
Group	Fracture pattern	Coronal	Middle	Total
Negative control	Horizontal	2	0	2
	Oblique	11	2	13
Positive control	Horizontal	0	0	0
	Oblique	15	0	15
GP/AH Plus	Horizontal	0	0	0
	Oblique	15	0	15
GP/Bioceramic	Horizontal	0	0	0
	Oblique	15	0	15
Core	Horizontal	3	0	3
	Oblique	12	0	12
Post/Core	Horizontal	2	0	2
	Oblique	13	0	13

Table 3. Fracture patterns and fracture locations in each group

Fig. 3 shows the survival probability as a function of fracture load using Weibull regression analysis. The fracture probability was highest in the positive control group and lowest in the negative control group. Compared to the GP/AH Plus and GP/Bioceramic groups, the core and fiber post/core groups had a somewhat greater survival probability.

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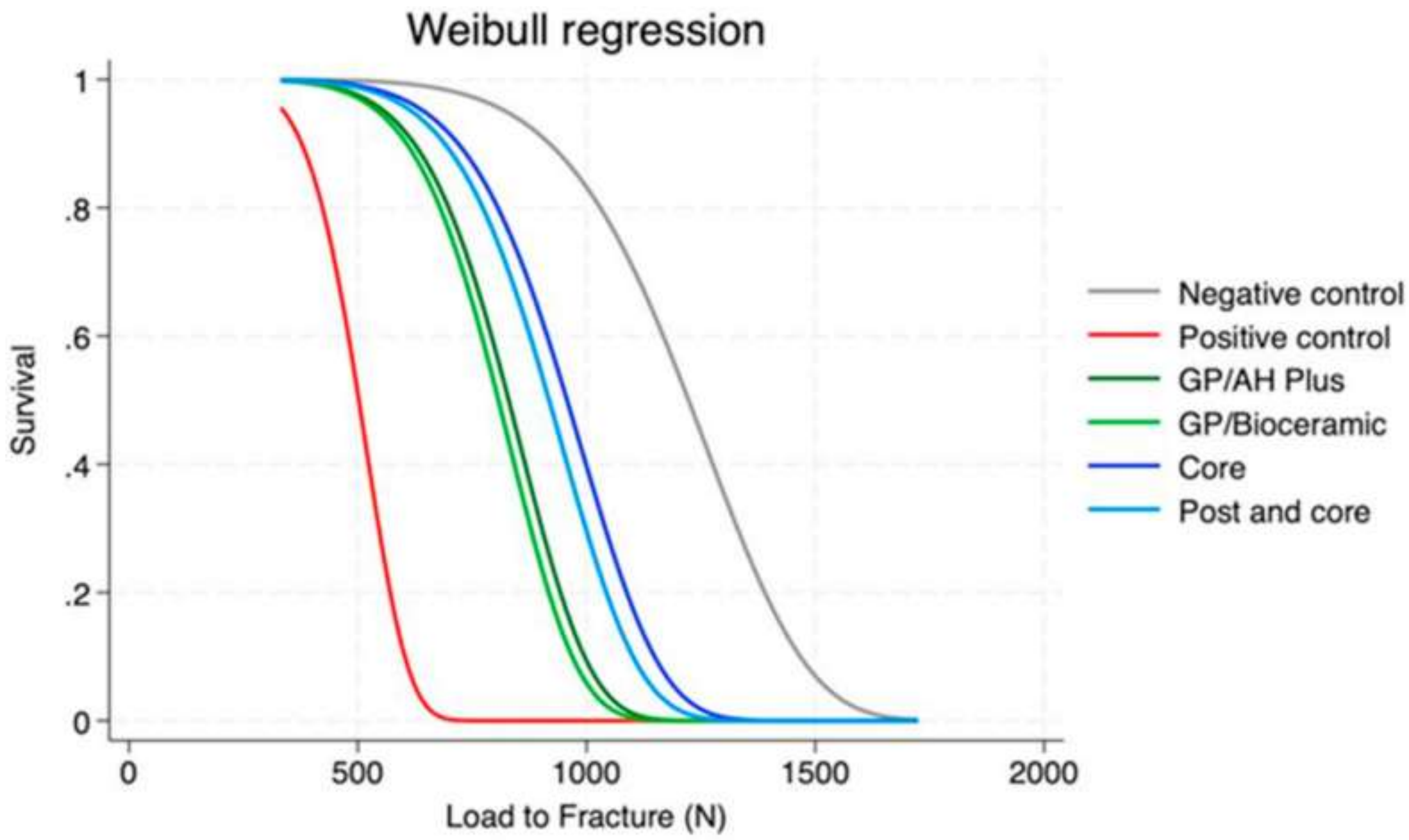

Figure 3. Weibull regression of survival curves for load to fracture (N) of different kinds of intraradicular filling materials.

DISCUSSION

After MTA apexification, we examined the effects of several intraradicular reinforcing materials on immature mandibular premolars. We rejected the null hypothesis since there was a substantial difference in fracture resistance between the experimental groups. The positive control showed the least amount of strength, whereas the intact tooth (negative control) showed the most.

Our results are consistent with other research demonstrating that fiber post/core and core restorations have greater fracture resistance than GP/AH Plus [4, 11, 22]. This is explained by the monoblock concept [23], which states that materials with dentin-like elasticity modulus improve bonding and load distribution. The majority of the included studies show increased fracture strength, according to a systematic review [24] and a narrative review [25]; this is probably because the fiber post/core materials' and the root dentin's similar modulus of elasticity allows for more uniform stress distribution within the root structure, allowing the restored roots to withstand higher occlusal loading. Conversely, GP/sealer has a lower modulus than root dentin, which leads to less efficient load distribution [26]. Furthermore, the hybrid layer and resin tags produced by the adhesive bonding technique fortify the root more efficiently than the micromechanical interlocking of bioceramic sealers [27]. Consequently, it is critical to use reinforcement materials that firmly cling to the root dentin and have a modulus comparable to that of natural tooth structure.

Some studies have shown the benefits of resin composite cores [6, 8, 11], while others have favored prefabricated posts [5, 10]. In line with Seto et al.'s findings at the 7-mm depth post/core and core group, we found no discernible difference in fracture resistance between core and fiber post/core [28]. There were no discernible variations in fracture resistance between the MTA, fiber post/core, and core groups, according to Linsuwanont et al. (2017) [4]. Regardless of the kind of tooth, all reinforcing techniques demonstrated noticeably greater fracture resistance than GP.Despite these similar results, the use of a fiber post may be especially advantageous in the case of young teeth. Immature teeth have weaker, structurally weakened roots, whereas mature teeth with less loss of coronal tissue do not always need a post. Even when the coronal structure is largely intact, fiber posts can be extremely important for boosting root strength and avoiding root fracture. This is corroborated by earlier studies showing how crucial post-placement is for improving the structural integrity of juvenile teeth [4, 5, 10].

There are benefits and drawbacks to both core and post/core. In core-only applications, polymerization shrinkage brought on by a large core volume is an issue. Dualcure materials are therefore advised to lessen stress [29]. Post-insertion decreases core volume to make up for shrinkage. Post-debonding [30] may result from the additional bonding contacts that this creates. According to one investigation, bond strength was not substantially impacted by increasing cement thickness [31]. According to our research, thick core materials increased polymerization stress is not a significant worry. However, by making sure that the material is positioned correctly, voids during core injection can be prevented.

In terms of fracture resistance, we found no difference between GP/AH Plus and GP/Bioceramic sealers. To improve adaptability, bioceramic sealers rely on the hydraulic pressure from matching GP cones [16, 32]. However, in juvenile roots with oval canals, matching GP cones is frequently not possible. Hydraulic pressure may be less important in immature teeth with a broader, open canal system because sealers may be able to adjust without precise GP matching.

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Even with mismatched GP cones, one investigation reported no discernible variations in the push-out bond strength between AH Plus and bioceramic sealer [18]. Our results demonstrate that, even though bioceramic sealers have a higher elastic modulus, proper elasticity and strong adhesion to the root dentin are essential for strengthening root canals.

Weibull analysis offers comprehensive insights into the distribution of material failures, in contrast to mean and standard deviation [20].It emphasised the likelihood that various intraradicular reinforcing materials would survive in the posterior mandibular region when subjected to the highest usual biting forces [33].Our results show that using reinforcement materials considerably increased the survival probability of immature roots following MTA apexification under normal occlusal stress. At biting forces of 676 and 918 N, untreated immature roots (positive control) did not survive (Fig. 4). It is crucial to use MTA apexification to reinforce the root canals of immature teeth to improve their survival and structural integrity. Superior protection against fractures, especially under severe biting forces, is suggested by the higher survival probability linked to core and fiber post/core.The efficiency of various reinforcement materials in extending the lifespan of MTA-apexified juvenile teeth may be revealed by assessing survival probabilities under particular biting stresses. However, the static forces that were replicated in our lab setting might not accurately represent chewing forces in real life, and more research is needed to determine the clinical applicability to a range of patient circumstances.

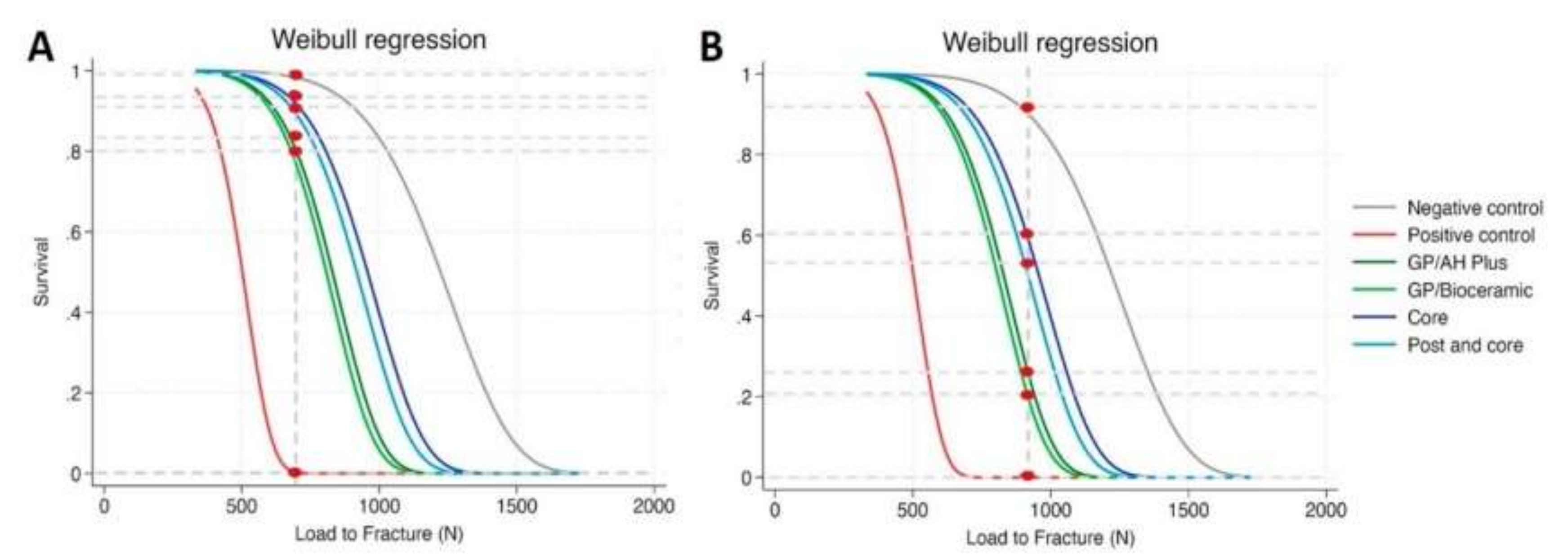

Figure 4. Weibull regression of survival curves for load to fracture (N) of different kinds of intraradicular filling materials at (A). 676 N and (B). 918 N.

Oblique fractures in the cervical root region were consistently produced by a 45° compressive load that mimicked occlusal forces in fracture pattern analysis. This finding was consistent with a study showing that the cervical root region experiences the majority of the occlusal load stress [34].Immature teeth are more prone to fractures in the peri-cervical region than mature teeth because oblique fracture happens where mechanical stress is greatest.

Compared to round canals, oval and long oval root canals undergo a larger distribution of stress [35]. We meticulously adjusted for root morphology characteristics in both the control and experimental groups to guarantee accuracy and consistency. Our study concentrated on the canal morphologies of lower premolars because they are typically oval or long oval in shape. Our limitations include simulating young teeth with mature structures and using static loading instead of dynamic loading, even though thermocycling and PDL models improve clinical relevance. Future studies should examine the effects of post-extension and composite core on fracture resistance, as well as use cyclic loading to more accurately simulate masticatory forces.

CONCLUSIONS

Within the parameters of this investigation, the use of intraradicular reinforcement materials (core and fiber post/core) in the MTA-apexified simulated immature teeth demonstrated superior reinforcement and survival effects compared to the use of traditional root-filling materials (GP/AH plus and GP/Bioceramic sealer).

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