RESEARCH PAPER

Comparative evaluation of marginal adaptation of pulp capping materials to dentin: A SEM analysis

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Abstract:

Background: Preservation of dental pulp vitality following trauma, deep caries, or restorative procedures remains a fundamental objective in conservative dentistry. Direct and indirect pulp capping procedures rely on biocompatible materials to maintain pulpal health, and their clinical performance is influenced by the quality of internal adaptation to dentin.

Aim: To evaluate and compare the internal adaptation of three commonly used pulp-capping materials—mineral trioxide aggregate (MTA), TheraCal LC, and Calcimol LC—to dentin using scanning electron microscopy (SEM).

Materials and Methods: This in vitro study included thirty extracted, caries-free human premolars that were randomly allocated into three groups ($n = 10$). Standardized Class I cavities were prepared in all specimens. The pulp-capping materials were applied according to manufacturers' instructions: Group 1 – MTA (Dentsply), Group 2 – TheraCal LC (Bisco), and Group 3 – Calcimol LC (Voco). Following material placement, all cavities were restored with a nanohybrid composite resin and subjected to 5,000 thermocycles to simulate oral conditions. The specimens were sectioned and examined under SEM. Internal adaptation at the pulpal floor was quantified using ImageJ software by calculating the percentage of de-bonded segments and measuring interfacial gaps.

Results:MTA demonstrated the highest level of internal adaptation, showing the smallest mean interfacial gap (3.00 ± 2.35 µm), followed by TheraCal LC (3.87 ± 1.52 µm). Calcimol LC exhibited the poorest adaptation, with the largest mean gap values (8.51 ± 2.04 µm). Statistical analysis using one-way ANOVA revealed a highly significant difference among the groups ($p < 0.001$), with Calcimol LC performing significantly worse than both MTA and TheraCal LC.

Conclusion:MTA exhibited superior marginal adaptation to dentin and continues to be considered the gold standard among the tested pulp-capping materials. TheraCal LC demonstrated comparable performance with added clinical handling benefits, making it a suitable alternative. Calcimol LC showed significantly inferior adaptation and may be less appropriate in clinical situations where optimal marginal sealing is essential.

Keywords: Pulp capping, TheraCal LC, MTA, Calcimol LC, Internal adaptation, Scanning Electron Microscopy

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INTRODUCTION

The preservation of dental pulp vitality is a primary objective in restorative dentistry, particularly when teeth are compromised by trauma, deep carious lesions, or previous dental treatments. In cases where decay extends significantly into the enamel and dentin layers, direct or indirect pulp capping procedures may be required. The choice between these techniques is largely determined by the extent of lesion penetration and its proximity to the pulp following caries removal.[1]

The overarching goal of vital pulp therapy is to maintain the natural health and function of the tooth, thereby avoiding more invasive interventions. Depending on the degree of pulpal involvement and its clinical condition, several treatment options may be considered, including direct pulp capping, indirect pulp capping, pulpotomy, and pulpectomy.[2]

Vital pulp therapy aims to preserve the pulp's vitality by applying a therapeutic material that promotes the formation of tertiary dentin, a biological barrier that protects and insulates the pulp against external stimuli.[3]

In direct pulp capping, a material is applied directly to an exposed pulp to encourage healing and maintain pulpal health.[4] In contrast, indirect pulp capping (IPC)is indicated when carious dentin is in close proximity to the pulp without actual exposure. In IPC, some affected dentin is intentionally left behind and covered with a biocompatible material to stimulate dentino-genesis and allow pulpal recovery. [5][6]

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Traditionally, calcium hydroxide (CH) has been widely used as the preferred material for pulp capping procedures in permanent teeth. Its efficacy is attributed to the release of hydroxyl ions, which induce a mild chemical injury that stimulates reparative dentin formation.[7] Despite its antimicrobial properties and ability to promote the release of growth factors, calcium hydroxide has notable limitations such as material degradation under restorations, cytotoxicity, and the formation of a porous dentin bridge.[8] These shortcomings have driven the development of newer materials with enhanced biocompatibility and durability. Among these alternatives, mineral trioxide aggregate (MTA) has shown superior clinical outcomes in terms of biocompatibility, dentin bridge formation, and pulp healing. However, MTA's clinical application is hindered by its long setting time, difficult handling, solubility issues, and high cost.[9]

In response to these limitations, light-cured, resin-modified calcium silicate-based materials such as TheraCal LC (Bisco Inc., USA) and Calcimol LC (Voco GmbH, Germany) have emerged. TheraCal LC, containing polymerizable methacrylates and calcium silicate, provides high calcium release and lower solubility than traditional materials, while supporting odontoblastic cell viability and dentino-genesis.[8] Calcimol LC, which combines calcium hydroxide with resin monomers, also releases calcium ions and offers convenient light-curing properties for clinical use.[10]

Achieving a reliable seal at the tooth-restoration interface is critical to preventing bacterial infiltration, recurrent caries, hypersensitivity, and eventual restoration failure. Internal adaptation of the pulp capping material to dentin plays a crucial role in this regard. Microleakage and poor adaptation compromise the longevity and clinical success of restorations.

Scanning Electron Microscopy (SEM) is a powerful tool used in both research and clinical settings to evaluate the marginal integrity and internal adaptation of dental materials. SEM provides high-resolution imaging that enables detailed assessment of microstructural features, adhesive failures, and material-tissue interfaces.[11]

Despite the availability of various pulp capping materials in the market, limited data exist regarding their internal adaptation to dentin. Accordingly, the objective of this in vitro investigation was to analyse and compare the internal adaptation of different pulp capping agents to dentinal surfaces using SEM evaluation.

The null hypothesis stated that no statistically significant difference would exist in the marginal adaptation of MTA, TheraCal LC, and Calcimol LC to dentin.

MATERIALS AND METHODOLOGY:

The present study was carried out in the Department of Conservative Dentistry and Endodontics in collaboration with Centre for Advanced Research at I.T.S. Centre for Dental Studies and Research, Muradnagar, Ghaziabad, Uttar Pradesh. The study has evaluated and compared the marginal adaptation of different pulp capping materials to dentin through SEM Analysis.

SPECIMEN PREPARATION

A total of 30 intact permanent premolars extracted for periodontal or orthodontic purposes were selected for this in vitro study. The collected teeth were cleaned thoroughly and disinfected using a 0.5% chloramine solution, followed by storage in distilled water at 4°C for a period not exceeding two weeks. To expose dentin, the occlusal surfaces were ground using 180-grit abrasive paper under continuous water irrigation with a LaboPol-25 polishing system (Struers, Denmark) until complete removal of the enamel layer was achieved. Subsequently, a standardized preparation depth of 1.5 mm was established using a marked bur, and further abrasion was performed to obtain a deep dentin surface.

Inclusion criteria	Exclusion criteria
Teeth extracted for- • Orthodontic or periodontal reasons • Non-carious, intact crowns and • Teeth free from restorations	• Anatomical developmental anomalies • Possibility of cracks, • Fractures

SAMPLE PREPARATION

Standardized Class I cavity preparations were created with dimensions of 3 mm depth, 3 mm mesiodistal width, and 4 mm buccolingual width. All cavities were prepared using a flat-ended cylindrical fine-grit diamond bur mounted in a high-speed contra-angle air turbine handpiece under constant water irrigation. Three pulp capping materials were included for evaluation: MTA (Dentsply), TheraCal LC (Bisco Inc., USA), and Calcimol LC (VOCO GmbH, Germany). The specimens were randomly distributed into three groups, with ten teeth allocated to each material. Detailed characteristics and clinical applications of the selected materials are presented in Table 1.The premolar teeth were randomly allocated into three groups (n = 30), and the specimens were further randomly distributed among the respective experimental groups.

GROUP 1(n=10)- MTA (DENTSPLY)

In Group 1, MTA was prepared according to the manufacturer's recommended protocol. The pulp-capping material was then placed into the cavity using a small-tipped amalgam carrier, followed by gentle compaction with an amalgam condenser to ensure proper adaptation.

GROUP 2 (n=10)- THERACAL-LC (BISCO)

In Group 2, TheraCal LC (Bisco, USA) was dispensed directly into the prepared cavity using the manufacturer-provided syringe tip in accordance with the manufacturer's instructions. Following placement, the material was light-cured for 20 seconds.

GROUP 3(n=10)- CALCIMOL-LC (VOCO)

In Group 3, Calcimol-LC was applied using an incremental technique, with each layer not exceeding 1 mm in thickness. Each increment was subsequently light-cured for 20 seconds.

APPLICATION OF RESTORATIVE MATERIAL

The remaining cavity space was restored using a universal adhesive system. The adhesive was uniformly applied to all prepared cavity walls with a microbrush, followed by gentle air thinning under moderate pressure for 5 seconds and subsequent light polymerization for 10 seconds. The restorative material was then inserted into the cavity in two successive increments, with each layer individually light-cured for 20 seconds. [11].

MTA requires 24-hour setting period under moist conditions before evaluation, whereas TheraCal LC and Calcimol LC are light-cured materials that allow immediate continuation**.** All samples are typically subjected to thermocycling and then analysed under SEM within 24–48 hours to evaluate marginal adaptation.

EVALUATION OF MARGINAL ADAPTATION

The specimens underwent thermocycling for 5,000 cycles between temperatures of 5°C and 55°C in distilled water, with a dwell period of 30 seconds in each bath. Following thermocycling, the teeth were sectioned perpendicularly through the center in a buccolingual orientation using a diamond disc. The exposed cross-sectional surfaces were sequentially finished under continuous water irrigation using abrasive papers of increasing grit sizes (600, 1,000, 1,500, 2,000, and 4,000; Sale Abrasives). Final polishing was carried out with a felt disc containing a 1.0 µm diamond suspension. To remove residual polishing particles, all specimens were ultrasonically cleaned in deionized water for 10 minutes.

Scanning electron microscopic (SEM) evaluation was conducted at the Centre for Nanoscience and Nanotechnology, Jamia Millia Islamia, New Delhi. Prior to imaging, the specimens were sputter-coated with gold, and micrographs were captured at magnifications ranging from 500× to 1000×. The acquired images were subsequently analyzed using the ImageJ software (National Institutes of Health, Bethesda, MD). The SEM scale bar served as a reference for measuring the extent of debonded regions along the pulpal floor, and the measured lengths were expressed as a percentage of the total pulpal floor length.[11]

STATISTICAL ANALYSIS

The data was entered into Microsoft Excel XP software program. Statistical analysis was done by Statistical Package for the Social Sciences (SPSS) software package (SPSS 16 Inc, Chicago IL, USA). The normality of data tested by Shapiro Wilk's test. The descriptive statistics mean, s.d. was calculated. The values obtained were statistically analyzed and to compare significance of difference of means of the parameters between groups were tested by parametric Oneway ANOVA followed by Bonferroni test for inter-group comparison and Paired t-test within the groups for normally distributed data and for not normal data Kruskal wallis test and Mann Whitney U test for Inter group comparison and Wilcoxon sign test for Intra group comparison will be used. The level of significance and confidence interval was 5% and 95% respectively, i.e $p< 0.05$. The error and power of study was 5% and 95 % respectively i.e $p< 0.05$.

*Significant $p<0.05$,

** Highly significant $p<0.01$

*** Very highly significant $p<0.001$

NS not significant $p>0.05$

RESULT

Table 2 shows the descriptive statistics provided for the marginal adaptation of the three materials (MTA, THERACAL, and CALCIMOL). MTA has the lowest mean marginal adaptation value (3.00 units); whereas, CALCIMOL has the highest mean value (8.51 units). Based on average performance (mean), MTA showed the best marginal adaptation, followed by THERACAL, with CALCIMOL showing the poorest adaptation.

Table 3 compares the marginal adaptation of the different materials (presumably) MTA, THERACAL, and CALCIMOL. The results of the One-way ANOVA test showed a statistically significant difference in the mean marginal adaptation among the three material groups (MTA, THERACAL and CALCIMOL) ($F(2,27$ and $29)=21.924$, $p<0.001$

The Table 4 and Figure 1 presents the results of pairwise comparisons of marginal adaptation among three materials: MTA, Theracal, and Calcimol, using a post hoc Tukey test. MTA and Theracal showed similar in marginal adaptation; whereas, Calcimol showed significantly inferior marginal adaptation compared to both MTA and Theracal.

Representative SEM images at different magnifications at 500x are presented in Figure 2-4. Continuous margins were observed along the pulp floor for MTA and Theracal LC. MTA and Theracal LC showed very small gap formations and gives a non-significant differences. The widest gaps were found with Calcimol-LC showing significant difference with MTA and Theracal LC.

DISCUSSION

Maintaining pulpal vitality is considered a key principle of conservative dental treatment. Procedures categorized under vital pulp therapy (VPT), particularly direct and indirect pulp capping techniques, aim to preserve pulp health and functionality following damage caused by carious processes, trauma, or operative procedures. The success of these interventions relies significantly on the ability of the pulp capping material to achieve a close, durable interface with dentin, thereby preventing

microleakage and facilitating the biological healing process. [12–14]
Historically, calcium hydroxide has served as the benchmark for pulp capping materials due to its antimicrobial properties and capacity to stimulate reparative dentin formation. However, its clinical shortcomings—including solubility, lack of adhesion, and the formation of porous dentin bridges—have prompted the development of bioactive materials with enhanced properties[15,16].
Among the newer generation of materials, mineral trioxide aggregate (MTA) has gained widespread clinical acceptance. Its excellent biocompatibility, sealing capacity, and bioactivity make it ideal for pulp capping procedures. In the present study, MTA demonstrated superior internal adaptation to dentin, as visualized under scanning electron microscopy (SEM). The tight interface observed is attributed to MTA's slight expansion during setting, which enhances its ability to seal dentin walls effectively[17–19]. The hydration reaction of tricalcium silicate in MTA promotes the release of calcium hydroxide, which subsequently facilitates the deposition of apatite-like crystalline structures, thereby enhancing its bioactive properties and improving sealing performance. [20,21] These findings are consistent with previous studies emphasizing MTA's capacity to support pulpal healing and dentin bridge formation[22–24].
Furthermore, the bioactivity of MTA plays a significant role in its improved performance. The hydration of tricalcium silicate particles leads to the release of calcium ions and the formation of calcium hydroxide, creating an alkaline environment that is conducive to hard tissue formation. These released ions interact with phosphate-containing tissue fluids to form apatite-like crystalline deposits along the dentin–material interface, promoting biomineralization and strengthening the seal [20,21]. The sustained calcium ion release also stimulates pulpal cell differentiation, reparative dentin formation, and dentin bridge deposition, thereby enhancing pulpal healing. These findings are in accordance with previous studies reporting that MTA provides favourable biological and physical properties for maintaining pulp vitality and improving long-term clinical outcomes.
TheraCal LC, a light-cured, resin-modified calcium silicate material, showed comparable internal adaptation to MTA. While SEM analysis did reveal some microgaps at the dentin interface, likely due to polymerization shrinkage, the differences were not statistically significant.[25,26] TheraCal LC benefits from ease of handling and immediate setting, making it clinically convenient. Additionally, the resin matrix absorbs water post-curing, continuing calcium ion release, which supports bioactivity[27,28]. Previous studies have reported favourable pulpal responses and comparable performance to MTA.[29–32] Despite its slightly lower bioactivity, TheraCal LC appears to be a viable alternative to MTA in cases requiring efficient handling and reduced chair time, particularly for indirect pulp capping.[33,34]
In contrast, Calcimol LC demonstrated significantly poorer internal adaptation, as confirmed by SEM imaging. The presence of substantial interfacial gaps and minimal integration with dentinal tubules indicates weak bonding and low sealing efficacy[12] These results may be attributed to its resin-based composition with limited calcium ion release, reducing its ability to stimulate reparative dentin.[15] Moreover, its degradation over time can compromise its sealing ability, increasing the risk of microleakage and subsequent pulpal complications[13]. These findings are consistent with studies reporting inferior biological response and reduced ion release compared to calcium silicate-based materials.[12,15]
In order to improve the clinical relevance of the study outcomes, the specimens were exposed to 5,000 thermocycling cycles ranging from 5°C to 55°C to reproduce thermal challenges similar to those occurring in the oral cavity.. This step aligns with established protocols and offers a more realistic assessment of the material's long-term sealing performance.[11,16] Thermocycling also serves to assess the stability of the material–dentin interface under repeated thermal fluctuations, which is considered an important determinant of restorative durability and clinical performance..[29]
The present study reinforces that the integrity of the dentin-material interface plays a pivotal role in the long-term clinical success of pulp capping procedures.[30–32] Materials like MTA that create a biologically active and mechanically stable seal show the most promising outcomes.[23,32] TheraCal LC, despite some limitations in interfacial bonding due to its resin component, can be considered a competent alternative due to its favourable handling characteristics and comparable sealing ability[31,32]. However, Calcimol LC appears less suitable for direct pulp capping due to its inadequate marginal adaptation and lower bioactivity.[12,15]

TABLE 1-Products tested in this study

Material manufacturer/ product type	Composition	Indication	Application procedure

MTA (Dentsply, TULSA, OK, USA)	Portland cement with added bismuth oxide and gypsum.	• Pulp Capping • Root Canal Perforation Repair • Apexification • Root-End Filling • Apexogenesis • Pulpotomy	• Preparing the area • Mixing the MTA with water or a specific solution, • Applying it to the desired location, ensuring it's kept moist during the setting process.
Theracal LC (Bisco) pulp protectant or liner	Portland cement, bisphenol A diglycidylmethacrylate, barium zirconate powder	Direct PC, indirect PC, deep cavity preparations (liner, base, and sealer)	1. Apply to operatory area of the preparation in incremental layers. 2. Layers are not exceeding 1 mm depth. 3. Light cure each increment for 20 s.
Calcimol LC (Voco) dentin liner	CH, urethane dimethacrylate, 2-dimethylaminoethyl methacrylate	Indirect PC, cavity liner	1. Apply to operatory area of the preparation in incremental layers. 2. Layers are not exceeding 1 mm depth 3. Light cure each increment for 20 s.

TABLE 2: Descriptive details of Marginal Adaptation

Material	**Mean**	**SD**	**SE**	**95% CI**
MTA	3.00	2.35	0.74	1.32-4.68
THERACAL	3.87	1.52	0.48	2.78-4.96
CALCIMOL	8.51	2.04	0.65	7.05-9.97

TABLE 3: Comparison of Marginal Adaptation

	Sum of Squares	**df**	**Mean Square**	**F**	**p-value**
Between Groups	175.496	2	87.748	21.924	<0.001*
Within Groups	108.063	27	4.002		
Total	283.559	29			

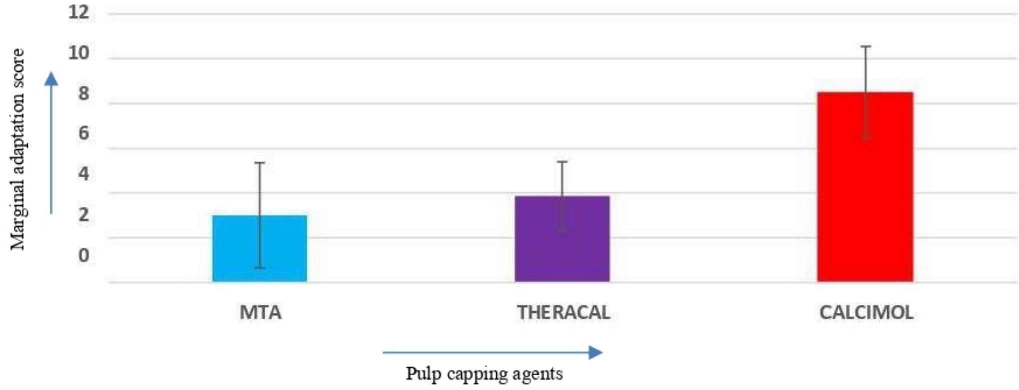
One-way ANOVA test; * indicates a significant difference at p≤0.05

TABLE 4: Pairwise comparison of Marginal Adaptation

Pairwise comparison	**p-value**
MTA vs Theracal	0.602
MTA vs Calcimol	<0.001*
Theracal vs Calcimol	<0.001*

Post hoc Tukey test; * indicates a significant difference at p≤0.05

FIGURE 1: Marginal Adaptation of MTA, Theracal lc and Calcimol lc



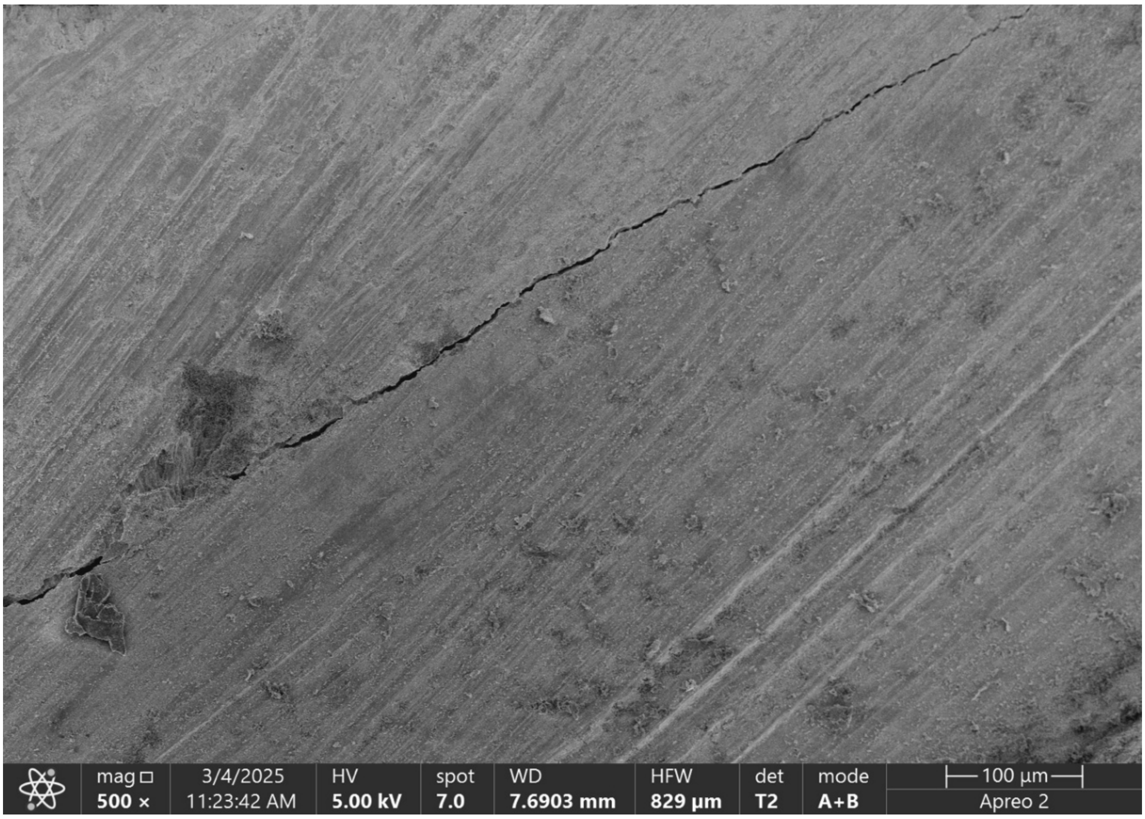


FIGURE 2: SEM IMAGE OF MTA AT 500X

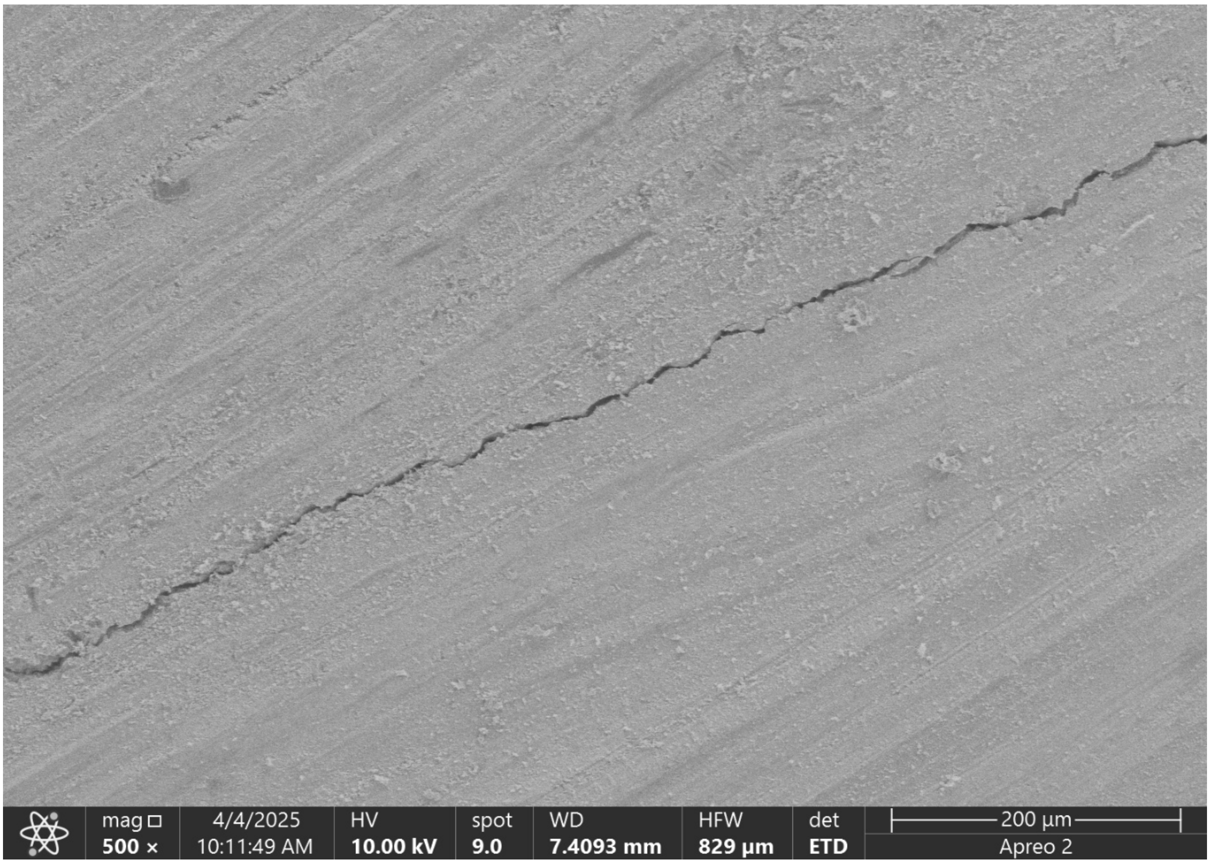


FIGURE 3: SEM IMAGE OF THERACAL LC AT 500X

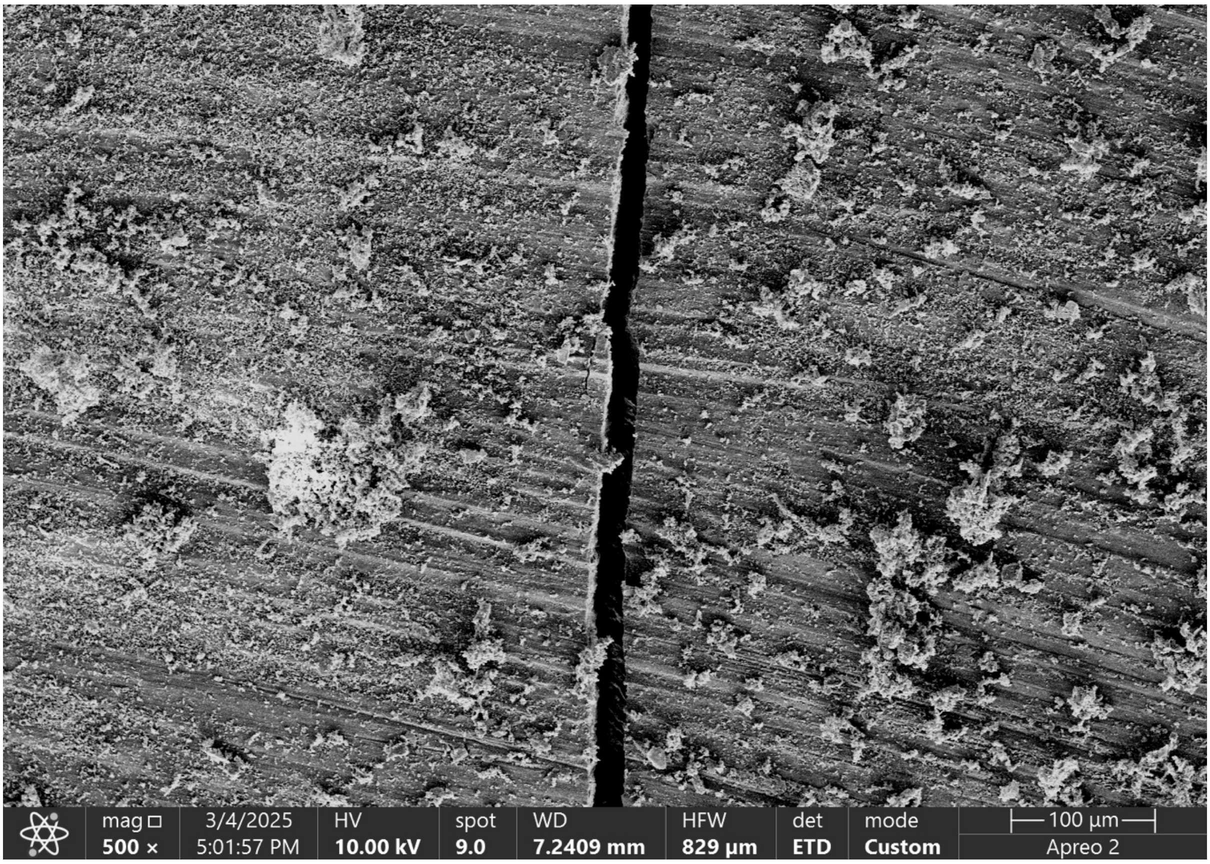


FIGURE 4: SEM IMAGE OF CALCIMOL LC AT 500X

LIMITATIONS AND FUTURE DIRECTIONS:

The study was conducted under in vitro conditions using a limited sample size (n=10 per group), which, although standardized, may not fully represent the complexity of intraoral conditions. Several clinical variables, including salivary contamination, functional occlusal loading, bacterial interactions, and individual patient-related factors, may affect the in vivo performance of pulp capping materials. Moreover, the limited duration of the present study does not permit evaluation of the long-term stability, durability, and biological responses associated with these materials.
Although the present findings provide meaningful information regarding the marginal adaptation and sealing capability of widely used pulp capping agents, additional clinical investigations involving larger sample populations and longer follow-up periods are warranted[14]. Such studies would enable a more comprehensive assessment of material behavior under clinical conditions, including their sustained influence on pulpal vitality and hard tissue repair.

CONCLUSION

This in vitro study compared the marginal adaptation of MTA, TheraCal LC, and Calcimol LC as pulp capping materials using SEM. MTA demonstrated the best marginal adaptation and remains the gold standard due to its superior sealing ability and bioactivity. TheraCal LC showed comparable adaptation, suggesting it may serve as a clinically viable alternative. Calcimol LC, however, exhibited poorer adaptation and reduced bioactivity. These findings underscore the importance of dentin-material interface integrity in pulp capping success. Further in vivo studies are needed to confirm these results and guide clinical application.

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Conflict of interest- none

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