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Radiopacity of Different Contemporary Pulp Capping Materials: An *In Vitro* Comparative Study

Güncel Farklı Pulpa Kaplama Materyallerinin Radyoopasitesi: *In Vitro* Karşılaştırmalı Bir Çalışma

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ABSTRACT

Aim: This study aimed to compare the radiopacity of different pulp capping materials using digital radiographic imaging.

Material and Methods: Eight different pulp capping materials were evaluated (n = 10 per group). Standardized disc specimens with a thickness of 1 mm and a diameter of 5 mm were prepared for each material. Radiographic images were obtained using a digital photostimulable phosphor system together with a 21-step aluminum step wedge and an enamel–dentin sample under standardized exposure conditions. The mean gray values obtained from the images were converted into millimeter aluminum (mm Al) equivalents. Statistical analysis was performed using one-way ANOVA followed by Tukey's post hoc test ($\alpha = 0.05$).

Results: Radiopacity values ranged from 1.911 ± 0.090 to 6.164 ± 0.312 mm Al, with significant differences among the materials ($p<0.001$). ProRoot MTA showed the highest radiopacity, whereas TheraCal LC exhibited the lowest values. Most materials met the ISO-recommended radiopacity threshold (≥3 mm Al); however, TheraCal LC, ApaCal ART, and MTA Cem LC remained below this level.

Conclusion: The radiopacity of pulp capping materials varies considerably depending on material composition. Because insufficient radiopacity may hinder radiographic detectability, this property should be considered alongside biological and handling characteristics when selecting pulp capping materials for clinical use.

Keywords: Pulp capping materials, radiopacity, calcium silicate, digital radiography, mean gray value.

ÖZ

Amaç: Bu çalışmanın amacı, farklı pulpa kaplama materyallerinin radyoopasitesini dijital radyografik görüntüleme kullanarak karşılaştırmaktır.

Gereç ve Yöntemler: Sekiz farklı pulpa kaplama materyali değerlendirildi (her grup için n = 10). Her bir materyal için 1 mm kalınlığında ve 5 mm çapında standart disk örnekleri hazırlandı. Radyografik görüntüler, standartlaştırılmış ışınlama koşulları altında 21 basamaklı alüminyum step-wedge ve mine-dentin örneği ile birlikte dijital fosfor sistemi kullanılarak elde edildi. Görüntülerden elde edilen ortalama gri değerleri milimetre alüminyum (mm Al) eşdeğerlerine dönüştürüldü. İstatistiksel analizler tek yönlü ANOVA ve ardından Tukey post hoc testi kullanılarak gerçekleştirildi ($\alpha = 0,05$).

Bulgular: Radyoopasite değerleri 1,911 ± 0,090 ile 6,164 ± 0,312 mm Al arasında değişti ve materyaller arasında istatistiksel olarak anlamlı farklılıklar bulundu ($p<0,001$). ProRoot MTA en yüksek radyoopasiteyi gösterirken, TheraCal LC en düşük değeri sergiledi. Materyallerin çoğu ISO tarafından önerilen radyoopasite eşiğini (≥3 mm Al) karşıladı; ancak TheraCal LC, ApaCal ART ve MTA Cem LC bu seviyenin altında kaldı.

Sonuç: Pulpa kaplama materyallerinin radyoopasitesi materyal kompozisyonuna bağlı olarak önemli ölçüde değişiklik göstermektedir. Yetersiz radyoopasitenin radyografik olarak ayırt edilebilirliği zorlaştırabileceği göz önünde bulundurulduğunda, pulpa kaplama materyallerinin seçiminde biyolojik ve kullanım özelliklerinin yanı sıra radyoopasite özelliği de dikkate alınmalıdır.

Anahtar kelimeler: Pulpa kaplama materyalleri, radyoopasite, kalsiyum silikat, dijital radyografi, ortalama gri değer.

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INTRODUCTION

Vital pulp therapy is a conservative treatment strategy intended to maintain pulp vitality when the tissue is exposed or at risk of exposure due to deep caries, trauma, or operative procedures. Maintaining pulp vitality allows continued dentin deposition and supports long-term tooth survival; therefore, appropriate material selection plays a critical role in treatment success (1).

In clinical practice, the success of pulp capping is assessed not only by the biological response but also by radiographic follow-up findings (2). Although biocompatibility and bioactivity are essential for dentin bridge formation, radiographic detectability is equally important for monitoring treatment outcomes. Clinicians should be able to clearly distinguish the capping material from enamel and dentin in order to detect marginal defects, secondary caries, or material loss (3).

Radiopacity is considered one of the key physical properties of dental materials (4). Materials with insufficient radiopacity may be difficult to differentiate from dental tissues and may lead to diagnostic errors (3). Radiopacity requirements for materials used in endodontic procedures, including pulp capping materials, have been established by the American National Standards Institute/American Dental Association and the International Organization for Standardization (ISO 6876:2012 and ISO 13116:2014). According to these guidelines, a 1-mm-thick material is expected to demonstrate radiopacity equivalent to at least 3 mm of aluminum (Al) on radiographic imaging (5-7).

Over time, various pulp capping materials have been introduced, with calcium hydroxide remaining the most well known and widely used option (8). More recently, tricalcium silicate based cements and resin-modified calcium silicate based materials have gained popularity (9). For these materials to be reliably distinguished from surrounding anatomical structures, they must exhibit adequate radiopacity. The radiopacity of pulp capping materials largely depends on the type and amount of radiopacifying agents incorporated into their composition. Radiopaque agents such as bismuth oxide, zirconium oxide, and barium sulfate are frequently incorporated into dental materials to improve X-ray attenuation (10). However, the level of radiopacity required for optimal clinical performance may vary depending on the material type (11).

Despite the wide range of available pulp capping materials, comparative data on their radiopacity remain limited, as many previous studies have evaluated only a small number of products or focused on specific material groups (9,11,12). Determining whether these materials provide sufficient radiographic contrast is clinically important for accurate diagnosis and follow-up.

Therefore, this study aimed to evaluate the radiopacity of various pulp capping materials. The null hypothesis was that the tested materials would not differ significantly.

MATERIAL AND METHODS

Ethical approval for the study was obtained from the Lokman Hekim University Scientific Research Ethics Committee (Approval No: 2025/299).

Sample Size Calculation

The sample size was calculated using G*Power software (version 3.1; Heinrich Heine University, Düsseldorf, Germany) for a one-way ANOVA model (fixed effects, omnibus). With an effect size of f = 0.44, $\alpha = 0.05$, and a power of 80%, at least 10 specimens per group were required; therefore, each group included 10 samples (n = 10).

Sample Preparation

Eight different pulp capping materials were evaluated. For each material, ten specimens (n = 10) were prepared, yielding a total of 80 standardized disc samples.

All materials were prepared according to the manufacturers' instructions and applied into Teflon molds measuring 5 mm in diameter and 1 mm in thickness. Light-cured resin-modified materials (TheraCal LC, Calcimol LC, MTA Cem LC, and ApaCal ART) and the dual-cured pulp capping material (TheraCal Putty) were polymerized using a light emitting diode (LED) (Woodpecker Led-B, China) light-curing unit for the duration recommended by the manufacturers.

Calcium silicate based materials (ProRoot MTA and Biodentine) and the calcium hydroxide based material (Dycal) were manually mixed and placed into the molds. The specimens were kept at 37 °C under 100% humidity for 24 hours to allow complete setting of the materials. The composition and application procedures of the tested materials are provided in Table 1.

Following the setting period, the samples were taken out of the molds. Thickness measurements were performed with a digital caliper, and any specimen that did not fall within the predetermined range (1.0 ± 0.1 mm) was excluded.

For radiopacity reference, an extracted human molar tooth was sectioned under water cooling with a low-speed diamond disc to obtain a 1 mm thick enamel–dentin slice. Before radiographic evaluation, the specimen was kept in distilled water at 37 °C for 24 hours.

Radiographic Procedure

Radiographic images were obtained using a 21-step aluminum step-wedge (99.5% purity) in accordance with ISO 4049:2019 standards with a focus-to-object distance of 30 cm. A wall mounted periapical X-ray unit (NewTom RxDC, NewTom CEFLA, Imola, Italy) was operated at 60 kVp, 8 mA, and an exposure time of 0.20 s. All images were acquired using No.2 photostimulable phosphor (PSP) plates (Carestream Health, Rochester, NY, USA).

The pulp capping specimens, enamel–dentin section, and aluminum step-wedge were radiographed simultaneously. A custom positioning device was used to standardize the focus-to-object distance and the spatial relationship between the PSP plate and the X-ray tube head, ensuring that the central X-ray beam was perpendicular (90°) to the PSP surface.

Following exposure, the PSP plates were immediately scanned using a dedicated imaging plate scanner (CS 7200, Carestream Dental, Atlanta, GA, USA) to obtain digital images. The radiographic procedure was repeated five times under identical conditions, and the same PSP plate was used for all exposures to minimize plate-related variability.

Table 1. Composition and application procedures of the pulp capping materials.

Material	Composition	Lot no	Application procedure
Dycal (Dentsply Sirona, USA)	Base: 1,3-butylene glycol disalicylate, zinc oxide, calcium phosphate, calcium tungstate; Catalyst: calcium hydroxide, zinc oxide, titanium dioxide, zinc stearate, N-ethyl-o/p-toluene sulfonamide	00015910	Mixed in equal volumes for 10 s; setting time: 2.5–3.5 min.
ProRoot MTA (Dentsply Sirona, USA)	Tricalcium and dicalcium silicate, tricalcium aluminate, bismuth oxide, calcium sulfate dehydrate or gypsum	0000212745	Mixed 1 package of powder and 1 ampoule of liquid for 1 minute.
Biodentine (Septodont, France)	Tricalcium silicate, aqueous calcium chloride solutions	B24818	5 drops of liquid/1 capsule and mix 30 seconds in the amalgamator and setting for 12 minutes.
TheraCal Putty (Bisco, USA)	Silicate glass-mix cement PEGDMA, Bis-GMA, Barium zirconate, Ytterbium Fluoride	2400012614	Syringe application; light-polymerized for 10 s (per 1 mm increment)
TheraCal LC (Bisco, USA)	Tricalcium and dicalcium silicate, calcium sulfate dehydrate, tricalcium aluminate, PEGDMA, Bis-GMA, barium zirconate.	2400014741	Light-polymerized for 20 s (per 1 mm increment)
ApaCal ART (Prevest DenPro, India)	calcium hydroxide, tricalcium phosphate, UDMA, TEGDMA, photoinitiators, hydroxyapatite, barium zirconate	3391805	Light-polymerized for 40 s (per 1 mm increment)
MTA Cem LC (Nexobio, Korea)	Bis-GMA, CaO, silica, barium sulphate (BaSO4)	ML231109	Light-polymerized for 20 s
Calcimol LC (Voco, Germany)	Calcium hydroxide, urethane dimethacrylate, 2-dimethylaminoethyl methacrylate	1848310	Light-polymerized for 20 s (per 1 mm increment)

Bis-GMA: Bisphenol A-glycidyl methacrylate; UDMA: urethane dimethacrylate; TEGDMA: triethylene glycol dimethacrylate; PEGDMA: polyethylene glycol dimethacrylate.

Measurement of Radiopacity Procedure

Using ImageJ software (National Institutes of Health, Maryland, USA), the mean gray values (MGV) of each aluminum step-wedge increment, pulp capping specimen, enamel, and dentin were measured on the digital radiographs (Figure 1).

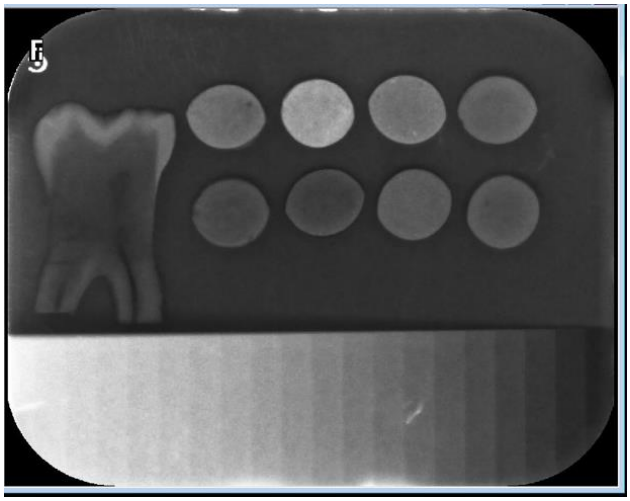


Figure 1. Digital radiographic image of the specimens and aluminum step-wedge.

For each specimen, three regions of interest (ROI) (10 × 10 pixels) were selected from homogeneous areas. MGV values were obtained using the "Analyze > Measure" function, and the mean of the three measurements was calculated. This procedure was repeated on ten radiographic images, and the overall mean was recorded for each material. The same protocol was applied to enamel, dentin, and each step of the aluminum step-wedge. To minimize observer bias, all measurements were performed by a single radiologist with six years of experience who was blinded to the material groups.

The radiopacity values of the samples were quantified in terms of millimeter aluminum equivalents (mm Al). For this purpose, the mean gray values (MGV) derived from the aluminum step-wedge were used, and the conversion was carried out based on the standardized approach reported in previous studies (3,13-15).

Statistical Analysis

IBM SPSS Statistics software (version 26.0; IBM Corp., Armonk, NY, USA) was used for statistical analysis. Normality and variance homogeneity were evaluated using the Shapiro–Wilk and Levene's tests. Group differences were assessed using one-way ANOVA with Tukey's post hoc test ($p<0.05$). Results are presented as mean ± standard deviation (SD).

RESULTS

Radiopacity values of the pulp capping materials ranged from 1.911 ± 0.090 to 6.164 ± 0.312 mm Al. Statistically significant differences among the materials were detected by one-way ANOVA ($p<0.001$) (Table 2).

Table 2. Radiopacity values of the tested materials expressed in millimeters of aluminum (mm Al) (mean ± SD).

Material	Radiopacity (mm Al) Mean ± SD
ProRoot MTA	6.164 ± 0.312[a]
Dycal	4.290 ± 0.152[b]
Biodentine	3.918 ± 0.189[c]
Calcimol LC	3.371 ± 0.215[d]
TheraCal Putty	3.206 ± 0.066[e]
TheraCal LC	1.911 ± 0.090[h]
MTA Cem LC	2.971 ± 0.183[f]
ApaCal ART	2.351 ± 0.150[g]
Dentin	2.122 ± 0.159[g]
Enamel	4.255 ± 0.328[b]

Different superscript lowercase letters indicate statistically significant differences between the groups (one-way ANOVA and Tukey's HSD test, $p<0.05$).

The radiopacity values of enamel and dentin were 4.255 ± 0.328 mm Al and 2.122 ± 0.159 mm Al, respectively.

ProRoot MTA demonstrated significantly higher radiopacity than all other tested materials as well as enamel and dentin ($p<0.001$). Dycal exhibited radiopacity comparable to enamel ($p>0.999$) but significantly higher than dentin ($p<0.001$).

Biodentine, Calcimol LC, TheraCal Putty, and MTA Cem LC showed radiopacity values significantly lower than enamel but significantly higher than dentin ($p<0.001$).

ApaCal ART presented radiopacity comparable to dentin ($p=0.055$).

TheraCal LC showed the lowest radiopacity and was significantly lower than all other materials ($p<0.001$).

DISCUSSION

This study evaluated the radiopacity of eight commonly used pulp capping materials from different material classes using digital radiography. The results demonstrated significant differences among the pulp capping materials, and the null hypothesis was rejected. Among the evaluated materials, ProRoot MTA exhibited the highest radiopacity, whereas TheraCal LC showed the lowest values.

According to the American National Standards Institute/American Dental Association (ANSI/ADA57:2021) and the International Organization for Standardization (ISO 6876:2012 and ISO 13116:2014), materials used in endodontic procedures are recommended to exhibit a radiopacity equivalent to at least 3 mm of aluminum for a 1-mm-thick specimen (5-7). Although these standards were originally developed for root canal sealers, they are widely used as a reference when assessing the radiopacity of pulp capping materials. In our study, most materials met this threshold, whereas some exhibited radiopacity values below the recommended level, which may compromise radiographic detectability in clinical practice.

The high radiopacity of ProRoot MTA can be attributed to the presence and proportion of radiopacifying agents in its composition. Mineral trioxide aggregate materials typically contain bismuth oxide, a high–atomic number compound that markedly increases X-ray attenuation (10,16). Previous studies have consistently reported that MTA-based materials demonstrate higher radiopacity than many calcium silicate–based alternatives, supporting the present findings (11,16,17). In contrast, materials such as Biodentine incorporate zirconium oxide as the radiopacifying component, which has been associated with comparatively lower radiopacity values (12,16,18). Differences in radiopacifier type, atomic number, and concentration are therefore considered primary determinants of the radiographic behavior of calcium silicate based materials (19).

Although both ProRoot MTA and MTA Cem LC are classified as mineral trioxide aggregate based products, ProRoot MTA demonstrated significantly higher radiopacity. This difference likely reflects variations in the type and proportion of radiopacifying agents in their compositions. ProRoot MTA has been reported to contain approximately 20% bismuth oxide, which substantially enhances X-ray attenuation (12). Such formulation differences among MTA based products may therefore translate into noticeable differences in radiographic visibility.

Overall, the present findings are in line with previous studies evaluating pulp capping and liner materials. Previous study has shown that MTA generally exhibits higher radiopacity, whereas TheraCal LC tends to present lower values (16). A similar result was observed in this study, further highlighting the strong influence of material composition and radiopacifier content.

TheraCal Putty demonstrated higher radiopacity than TheraCal LC. TheraCal LC is a light-cured material, whereas TheraCal Putty is a dual-cure setting reaction. Differences in curing mechanism, along with variations in resin matrix composition, filler characteristics, and the type and proportion of incorporated radiopacifiers, may have contributed to the observed disparity in radiopacity. Previous reports have likewise indicated that materials within the same product family can exhibit substantially different radiographic behavior depending on their specific formulation (16,19).

ApaCal ART demonstrated radiopacity values comparable to dentin. This finding may be related to its composition. Besides calcium hydroxide and tricalcium phosphate, the material contains hydroxyapatite, which is chemically similar to the mineral phase of dentin and may contribute to comparable X-ray attenuation. In addition, the radiopacity of resin-containing materials is known to depend heavily on the type and proportion of radiopacifiers such as barium zirconate (11,12), which may partly explain the relatively lower values observed for this material.

When the materials were evaluated within their categories, conventional calcium hydroxide and calcium silicate based materials generally showed higher radiopacity than resin-containing counterparts. For example, the conventional calcium hydroxide material Dycal showed higher radiopacity than the resin-modified Calcimol LC. A similar tendency was observed among calcium silicate materials, where traditional formulations such as ProRoot MTA and Biodentine demonstrated greater radiopacity than most resin-modified products. This trend may be explained by the higher inorganic filler content of conventional materials, whereas the presence of an organic resin matrix may dilute the relative proportion of radiopaque fillers (20). Nevertheless, radiopacity remains formulation-dependent, and variations may occur among individual products.

Comparison with natural dental tissues provides clinically relevant context for interpreting radiopacity values. In this study, ProRoot MTA showed radiopacity higher than

enamel, while Dycal was comparable to enamel. Several materials presented radiopacity between enamel and dentin, while TheraCal LC showed values lower than dentin. Since secondary caries is a major reason for restoration replacement, adequate radiopacity of base and liner materials is essential to create sufficient contrast with recurrent caries and adjacent tooth structures (13). Materials with moderate radiopacity ideally slightly higher than enamel have been suggested to provide optimal diagnostic visibility. In this context, materials with radiopacity close to or below dentin may be more difficult to identify radiographically (13,16). Therefore, radiopacity should be considered together with biological and handling properties when selecting pulp capping materials.

Radiopacity is not only a physical property of a material but also an important factor that directly affects clinical interpretation during radiographic follow-up. Materials with sufficient radiopacity can be clearly distinguished from surrounding dental tissues, allowing clinicians to evaluate marginal adaptation and detect secondary caries or material loss that may not be visible during clinical examination. Radiographic assessment is known to reveal many restoration-related problems that cannot be identified clinically alone (13,19).

In vital pulp therapy, the evaluation of treatment success relies on both clinical and radiological findings, particularly for monitoring healing and dentin bridge formation over time (17). When the radiopacity of a material is close to or lower than that of dentin, it may become difficult to differentiate it from adjacent structures, which can reduce diagnostic accuracy and delay appropriate intervention (9,13).

On the other hand, very high radiopacity may also be problematic, as it can mask underlying structures and make the detection of recurrent caries more difficult. For this reason, a moderate level of radiopacity, ideally similar to or slightly higher than enamel has been suggested to provide optimal radiographic visibility (9,19). From a clinical perspective, these findings indicate that radiopacity should be considered not only as a material characteristic, but also as a key factor in ensuring reliable diagnosis during long-term follow-up.

This study has some limitations. The in vitro design, although useful for standardization, cannot fully replicate the complexity of clinical radiographic conditions. Only a single material thickness (1 mm) was evaluated, and clinical variations in material thickness may influence radiographic appearance and radiopacity values. Previous studies have shown that increasing material thickness results in higher radiopacity values due to greater X-ray attenuation (3,21). Conversely, thinner layers may exhibit lower radiopacity and may be more difficult to distinguish from surrounding dental tissues. In clinical conditions, variations in the thickness of pulp capping materials may therefore affect their radiographic visibility and interpretation (16). Although a standardized thickness of 1 mm was used in the present study in accordance with ISO recommendations, it should be considered that different clinical applications may involve variable material thicknesses. This may influence the radiographic appearance and detectability of the material. Therefore, future studies evaluating radiopacity at different thicknesses would provide additional clinically relevant information and improve the translation of in vitro findings to clinical practice. In addition, differences among imaging systems and exposure parameters may affect radiopacity measurements. Finally, the study focused solely on radiopacity and did not examine other clinically relevant properties such as sealing ability, bioactivity, or long term clinical performance. Future studies incorporating different imaging conditions and broader material assessments would help provide a more comprehensive understanding of clinical behavior.

CONCLUSION

Within the limitations of this in vitro study, the radiopacity of contemporary pulp capping materials varied significantly according to their composition. ProRoot MTA demonstrated the highest radiopacity, whereas TheraCal LC exhibited the lowest values. Most of the tested materials met the ISO recommended radiopacity threshold; however, TheraCal LC, ApaCal ART, and MTA Cem LC showed values below this level. Conventional calcium silicate and calcium hydroxide based materials generally tended to present higher radiopacity than resin-containing counterparts. Since radiographic detectability is important during clinical follow-up, radiopacity should be considered along with biological and handling characteristics when choosing pulp capping materials.

DECLARATIONS

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Use of AI Tools: The authors declare that no Artificial Intelligence (AI) tools were used in the creation of this article.

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