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Comparative Radiopacity Evaluation of Dental Materials Used in Vital Pulp Therapy

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Abstract

Background: Radiopacity is an essential property of pulp capping materials, enabling accurate radiographic diagnosis and differentiation from dental tissues. This study compared the radiopacity of 15 dental materials used in vital pulp therapy of primary and permanent teeth with each other and with enamel and dentin.

Methods: Eight calcium silicate-based, 6 glass ionomer-based, and 1 calcium hydroxide-based material were tested. Forty-five disk-shaped specimens (8 mm diameter, 2 mm thickness) were prepared according to manufacturers' instructions. Radiographs were obtained using digital radiography with enamel, dentin sections, and a 9-step aluminum (Al) wedge. Mean gray values were converted to equivalent Al thickness (mm Al) using calibration curves. Data were analyzed using 1-way ANOVA and Tukey's post hoc test ($\alpha = 0.05$).

Results: Significant differences in radiopacity were found among materials ($P < .001$). Bio-C Repair and NeoPutty MTA showed the highest mm Al values, while Amalgomer and Zirconomer had the lowest. Ionofil U, Glass Liner, Theracal LC, Calcimol LC, Amalgomer, and Zirconomer had radiopacity lower than both primary and permanent enamel.

Conclusion: All calcium silicate-based materials met the ISO 6876 threshold of ≥3 mm Al. However, the radiopacity of Amalgomer and Zirconomer was lower than that of dentin and below acceptable clinical standards.

Keywords: Calcium silicate cement, dental materials, glass ionomer cement, radiopacity

What is already known about this topic?

- *Adequate radiopacity is essential for distinguishing dental materials from dental tissues and detecting secondary caries. Materials that fail to meet the standards clinically expected of dental materials may compromise radiographic diagnosis.*

What does this study add to this topic?

- *Although several studies have compared the radiopacity of calcium silicate- and glass ionomer-based materials using permanent teeth, no study to date has evaluated these materials in comparison with primary teeth.*
- *Therefore, this study offers insights for clinicians in selecting materials that ensure radiographic visibility and diagnostic accuracy in both primary and permanent teeth.*
- *Clinicians should consider radiopacity during material selection, particularly in pulp therapies of primary and permanent teeth.*

INTRODUCTION

During the removal of deep dentinal caries, there is a risk of pulp perforation. Pulpal exposure may also occur as a result of dental trauma. In such cases, the modern treatment approach should focus on preserving the vitality of the healthy pulp tissue.[1,2] Vital pulp therapies (VPTs), such as indirect pulp capping, direct pulp capping, and pulpotomy, are procedures aimed at preserving pulpal vitality. The maintenance of tooth vitality is achieved through the formation of reparative dentin by covering the pulp tissue with biocompatible materials.[3] Various restorative materials with different properties are used in VPT.

Calcium hydroxide has been a preferred material for VPTs for many years.[4] However, it induces hard tissue barrier formation slowly, and the resulting reparative dentin tends

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to be structurally irregular. Moreover, calcium hydroxide does not bond to dentin and is subject to dissolution over time.[3,4] Mineral trioxide aggregate (MTA) is the first calcium silicate-based cement known for its excellent sealing ability and stimulation of hard tissue formation. MTA has various clinical applications, including root canal repair, apical plugging, and pulp capping. Nevertheless, it presents several disadvantages such as handling difficulty, prolonged setting time, and potential tooth discoloration. In recent years, numerous calcium silicate-based cements with modified compositions have been developed to overcome these limitations.[4] Conventional glass ionomer cements (GICs) can form ionic bonds with dental tissues and are capable of fluoride release.[5] Due to their ease of manipulation and acceptable aesthetics, conventional GICs are frequently used to restore posterior primary teeth.[6] To overcome the disadvantages of conventional GICs, modified materials such as Zirconomer (zirconia-reinforced GIC) and Amalgomer (ceramic-reinforced GIC) have been developed.[7,8]

The radiopacity of dental materials is essential for the clinical evaluation of restorations, detection of secondary caries, and identification of pulpal boundaries.[1] Additionally, materials should have radiopacity that is distinguishable from dental tissues and equal to or greater than that of dentin.[9] Several factors influence radiopacity, including the type of radiopaque element added to the material, specimen thickness, and exposure time of the radiographic device used.[1,10,11]

There are studies in the literature evaluating the radiopacity of certain materials used in VPT. [1,12-14] Such studies typically compare material radiopacity to that of enamel and dentin in permanent teeth.[12,15-19] Primary teeth have less enamel and dentin thickness compared to permanent teeth. Moreover, the organic and inorganic composition, as well as the degree of mineralization of primary teeth, differs from those of permanent teeth.[20] Therefore, the aim of this study was to evaluate the radiopacity of 15 different dental materials used in VPT for primary and permanent teeth, and to compare these values with the enamel and dentin of both dentitions. To the best of knowledge, there are only a limited number of studies in the literature that compare the radiopacity of dental materials with both primary and permanent tooth structures.[21] In this respect, the present study aims to provide a valuable contribution to the literature by evaluating a broad range of materials with different compositions using a standardized methodology. The null hypothesis of the study is that there would be no significant differences in radiopacity among the tested materials and between the materials and the enamel and dentin of primary and permanent teeth.

MATERIAL AND METHODS

Ethical Approval

Q2 This study was approved by the Non-Pharmaceutical and Non-Medical Device Research Ethics Committee of the Faculty of Dentistry, Necmettin Erbakan University (Approval No: 2024/522; Date:26/12/2024). In this study, extracted and anonymized human primary teeth that had previously been removed for various clinical reasons unrelated to the research were used. Written informed consent is routinely obtained from patients at the time of tooth extraction as part of standard clinical protocol. Therefore, no additional consent specific to the study was required.

Specimen Preparation

Fifteen different dental materials were tested in this study. The contents of the tested materials are presented in Table 1. A total of 45 disk-shaped specimens (8 mm in diameter, 2 mm in thickness) were prepared using a standardized mold, following the manufacturers' instructions (n=3).[15,19]

An extracted third molar (for orthodontic reasons) and an exfoliated primary molar (with completed physiological root resorption) were used to obtain enamel and dentin samples. The teeth were cleaned, and the roots of the permanent tooth were sectioned below the cementoenamel junction. Using a low-speed diamond saw under water cooling (Isomet, Buehler Ltd., Lake Bluff, IL, USA), the teeth were sectioned longitudinally to obtain enamel and dentin specimens with a thickness of 2 mm.

Radiographic and Densitometric Procedure

To ensure standardization, a 9-step aluminum (Al) step wedge with 1 mm incremental thicknesses was prepared. The Al step wedge was used to determine the radiographic density of the tested specimens in terms of Al equivalent thickness (mm Al). For radiographic evaluation, all samples—including the 15 different dental materials, primary and permanent tooth sections, and the Al step wedge—were positioned on a size 4 phosphor plate (5.7 × 7.5 cm, Carestream Dental) (Figure 1). The phosphor plate was placed 30 cm away from the X-ray source. Exposure settings were standardized at 60 kVp, 7 mA, and 0.20 seconds. The phosphor plates were then scanned using a phosphor plate scanner (CS7600, Carestream Dental). The digital images were transferred to ImageJ software (National Institutes of Health) for analysis. In the digital image, the radiopacity measurements were performed on each mm step of the Al wedge, as well as on the test specimens and enamel/dentin sections, by selecting 3 different regions of interest (1 mm^2 or 10 × 10 pixels). The mean gray value (MGV) was recorded for each measurement. The average of 3 separate MGV readings was calculated for each specimen, and the procedure was repeated independently on 2 separate radiographic images. The mm Al values for each step of the wedge, test materials, and enamel/dentin samples were calculated using the corresponding MGVs and the Mycurvefit application.[22] The MGVs were then converted into equivalent Al thicknesses using a calibration curve-based formula.[23]

Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 27.0 (IBM Corp., Armonk, NY, USA), with the level of significance set at 0.05. The normality

Table 1. Composition of Tested Dental Materials

Material	Composition	Manufacturer
Ionofil U	Mixture of different dimethacrylates (bis-GMA, UDMA), silicates, pigments and catalyst system	VOCO GmbH, Cuxhaven Germany
Equia Fort HT	Powder: Fluoro-alumino-silicate glass, polyacrylic acid, pigment. Liquid: Water, polyacrylic acid, carboxylic acid	GC Tokyo Japan
Riva Light Cure	Liquid: acrylic acid homopolymer; 2-hydroxyethyl methacrylate; dimethacrylate cross-linker; acid monomer; tartaric acid. Powder: Fluoroaluminosilicate glass powder	SDI Limited, Victoria, Australia
Glass Liner	Qualitative composition: Glass ceramic, glass ionomer powder, silica, camphorquinone, hexanediol dimethacrylate, Bis-GMA, BHT, DMTBA Quantitative composition: Fillers 65%; activators, accelerators and stabilizers 1%, dimethacrylates 34%	WP Dental, Germany
Theracal LC	Calcium silicates (Portland cement type III), Bis-GMA (Bisphenol A diglycidyl methacrylate), PEGDMA (Polyethylene glycol dimethacrylate) and Barium zirconate	Bisco, Schaumburg, IL, USA
Theracal PT	Base: silicate glass-mix cement, polyethylene glycol Di methacrylate, Bis-GMA, barium zirconate Catalyst: barium zirconate, ytterbium fluoride, initiator	Bisco, Schaumburg, IL, USA
Thera Base Ca	Portland cement, ytterbium glass with barium, ytterbium fluoride and Bis-GMA	Bisco, Schaumburg, IL, USA
Calcimol LC	Light-curing radiopaque 1-component material containing urethane dimethacrylate resin, calcium dihydroxide, dimethylaminoethyl-methacrylate, and TEGDMA	VOCO GmbH, Cuxhaven Germany
MTA Repair HP	Powder: Tricalcium Silicate, Dicalcium Silicate, Tricalcium Aluminate, Calcium Oxide, Calcium Tungstate Liquid: Water and Plasticize	Angelus, Londrina, Parana, Brazil
Bio-C Repair	Calcium silicate, calcium oxide, zirconium oxide, iron oxide, silicon dioxide, dispersing agent	Angelus, Londrina, Parana, Brazil
NeoPutty MTA	Tricalcium silicate, dicalcium silicate, tantalium oxide	NuSmile, Houston, TX, USA
Biodentin	Powder: Tricalcium silicate, Dicalcium silicate, Calcium carbonate, Iron oxide and Zirconiumoxide. Liquid: Water, Calcium chloride and modified polycarboxylate	Septodont, France
Endocem MTA	Calcium oxide, silicate oxide, aluminum oxide, other metallic oxides, bismuth oxide	Maruchi USA
Amalgomer	Powder: Fluoro-aluminosilicate glass, polyacrylic acid powder, tartaric acid powder and ceramic-reinforced powder and zirconium oxide. Liquid: Polyacrylic acid and distilled water	Advanced Healthcare Ltd. Tonbridge, England
Zirconomer	Powder: aluminofluorosilicate glass, zirconium oxide, tartaric acid Liquid: polyacrylic acid, deionized water	Shofu INC, Kyoto, Japan

of data distribution was assessed using the Shapiro–Wilk test, and all groups were found to follow a normal distribution. Therefore, 1-way analysis of variance (ANOVA) was used to compare the radiopacity values among the tested groups. Tukey's post hoc test was applied to identify statistically significant differences between specific group pairs.

RESULTS

The mean and standard deviation values of the MGV and equivalent Al thickness (mm Al) for each group are presented in Table 2. The mm Al values of the tested groups, ranked from highest to lowest, were as follows:

Neo MTA > Bio-C Repair > Endocem MTA > MTA HP Repair > Riva SC > TheraBase Ca > Equia Forte HT > Biodentin > Permanent Enamel > Primary Enamel > Theracal PT > Theracal LC > Calcimol LC > Glass Liner > Primary Dentin > Ionofil U > Permanent Dentin > Zirconomer > Amalgomer.

A statistically significant difference was found among the groups ($P < .001$). Amalgomer and Zirconomer exhibited lower mm Al values than both primary and permanent dentin. Ionofil U showed a lower mm Al value than primary dentin but a higher value than permanent dentin ($P < .001$). The Ionofil U, Glass Liner, Theracal LC, Calcimol LC, Amalgomer, and Zirconomer groups showed mm Al values lower than both primary and permanent enamel ($P < .001$). Theracal PT exhibited mm Al values similar to those of primary and permanent enamel ($P > .001$). NeoPutty MTA, Bio-C Repair, Endocem MTA, MTA HP Repair, Biodentin, TheraBase Ca, Riva SC, and Equia Forte HT showed significantly higher mm Al values than both primary and permanent enamel ($P < .001$).

DISCUSSION

In this study, significant differences in the radiopacity values of the evaluated dental materials were observed. Since some materials exhibited lower radiopacity than the enamel and dentin of both primary and permanent teeth, the null hypothesis was partially rejected.

Radiopacity is a critical property for the clinical assessment of dental materials. It plays a major role in evaluating the adaptation between the restoration and the tooth, detecting secondary caries under restorations, and identifying the boundaries of pulpal tissues on radiographic images.[24] For accurate diagnosis in clinical practice, restorative materials should possess sufficient radiopacity to be clearly distinguishable from natural dental tissues.[25] Therefore, the present study assessed the radiopacity of various dental materials

Table 2. Mean and Standard Deviation Values of MGV and mm Al Values of Tested Dental Materials

Material	Mean MGV ± SD	Mean mm Al ± SD	Manufacturer Given Radiopacity Value
Amalgomer	107.0 ± 1.6	1.96 ± 0.06[a]	Radiopaque
Zirconomer	108.3 ± 4.3	2.01 ± 0.1[a]	Radiopaque
Permanent dentin	112.9 ± 3.5	2.19 ± 0.14[b]	
Ionofil U	120.9 ± 50	2.49 ± 0.19[c]	None
Primary dentin	125.3 ± 3.2	2.66 ± 0.12[d]	
Glass liner	142.4 ± 2	3.37 ± 0.09[e]	Radiopaque
Calcimol LC	153.8 ± 1.9	3.87 ± 0.08[f]	180% Radiopaque
Theracal LC	171.1 ± 3.4	4.53 ± 0.13[g]	Radiopaque
Theracal PT	173.8 ± 2.3	4.63 ± 0.09[g,h]	Radiopaque
Primary enamel	174.9 ± 6.1	4.68 ± 0.23[h]	
Permanent enamel	175.1 ± 2.0	4.68 ± 0.07[h]	
Biodentin	181.9 ± 4.3	4.94 ± 0.16[i]	None
Equia Forte HT	184.6 ± 4.6	5.05 ± 0.2[i]	Radiopaque (2.6 mm Al for 1 mm)
TheraBase Ca	189.1 ± 1.4	5.25 ± 0.06[j]	Radiopaque
Riva SC	205.5 ± 2.5	6.02 ± 0.15[k]	Radiopaque
MTA HP repair	233.1 ± 2.2	7.83 ± 0.16[l]	Nearly matches that of gutta-percha. More radiopaque than dentine and bone
Endocem MTA	248.0 ± 1.4	8.84 ± 0.09[m]	Equivalent to 3 mm of Al or more in thickness Radiopaque
BİO-C repair	251.9 ± 0.4	9.27 ± 0.07[n]	≥7 mm of the aluminum scale
NeoPutty MTA	254.5 ± 0.3	9.73 ± 0.05[n]	Radiopaque

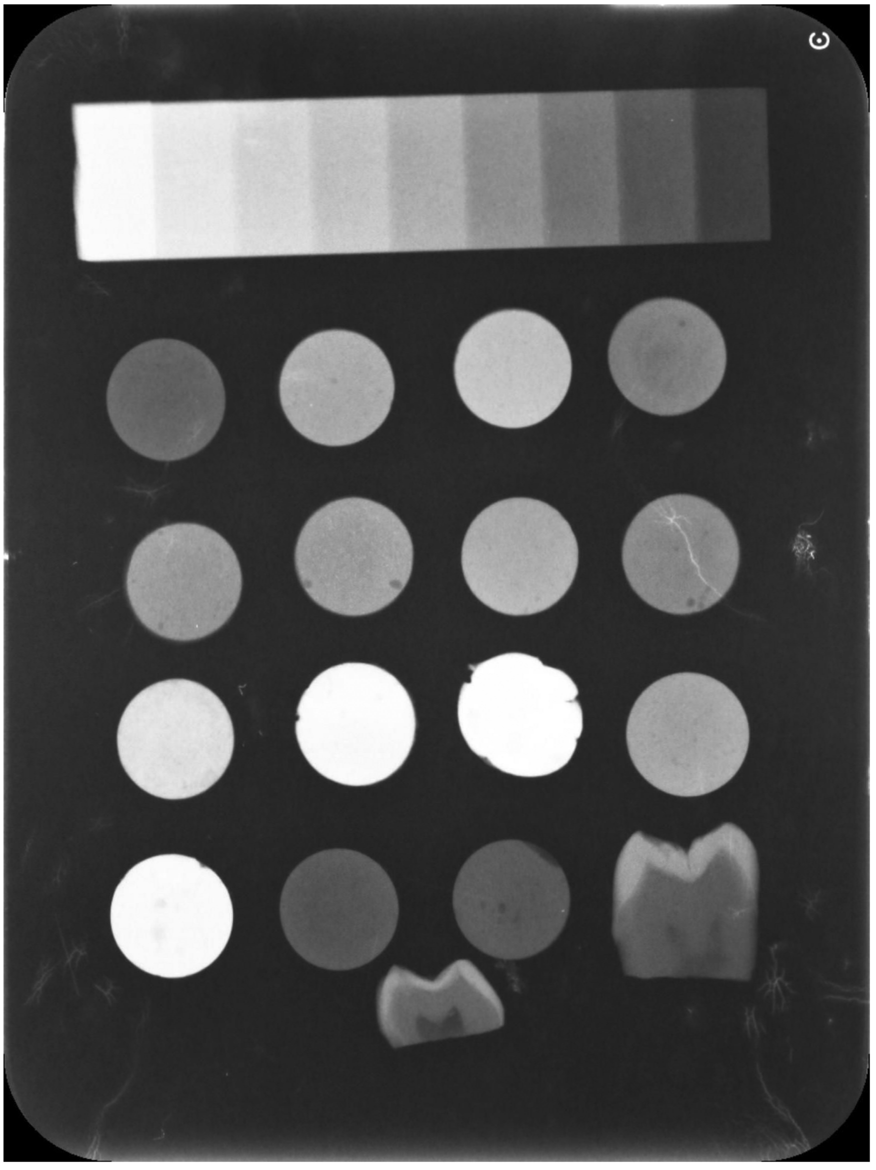
Statistical differences are indicated by different superscript letters ($P < .001$).

commonly used in VPT procedures in both primary and permanent teeth.

Primary and permanent teeth differ in both morphological and histological aspects.[20] These structural differences may influence how dental materials interact with surrounding tissues on radiographic imaging. As a result, the same material may exhibit different radiopacity values depending on whether it is compared to primary or permanent tooth tissues. In light of this, the present study evaluated the radiopacity of each material relative to both primary and permanent enamel and dentin, allowing for a more comprehensive and clinically relevant assessment. In this context, the present study aimed to provide a more comprehensive evaluation by assessing the radiopacity of each material relative to both primary and permanent enamel and dentin.

Digital or conventional radiographic techniques can be used to assess radiopacity.[26] Digital systems are often preferred due to several advantages over conventional methods, including reduced radiation exposure, faster image acquisition, and the ability to view and store images on the same device.[27] In digital radiography, each pixel in the image corresponds to a grayscale value ranging from 0 to 255. Radiopacity values are calculated by converting these grayscale values into equivalent Al thickness (mm Al) using appropriate software.[10] In the present study, the radiographic images of the dental materials were obtained using a digital radiography system. The radiopacity of the tested materials was determined according to standards published by the International Organization for Standardization (ISO 13116:2014, ISO 6876:2012, and ISO 9917:2017).[28-30] According to ISO 13116, pure Al is used as a reference material in the evaluation of dental materials' radiopacity. Aluminum has been reported to exhibit similar radiopacity to that of dentin.[28] Previous studies have also shown that 1 mm of enamel is approximately equivalent to 2 mm of Al, and that dentin and Al have comparable radiopacity when measured at the same thickness.[1,10,15] The use of an Al step wedge is considered the standard method for radiopacity comparison.[31] In this study, radiopacity values of the materials were compared using both an Al step wedge and sections of enamel and dentin from primary and permanent teeth. The enamel of primary and permanent teeth exhibited similar radiopacity. However, primary dentin showed greater radiopacity than permanent dentin, which may be attributed to its lower tubular density and smaller tubule diameter despite its lower mineral content.[32]

According to ISO 6876, root canal filling materials should exhibit a radiopacity equal to or greater than 3 mm Al for a specimen with a thickness of 1 mm.[29] In the present study, all tested calcium silicate-based materials demonstrated radiopacity values exceeding 3 mm Al. Biodentine showed a radiopacity of 4.94 ± 0.16 mm Al, which meets ISO 6876 requirements. Previous studies have reported radiopacity values for Biodentine ranging from 1.5 to 4.1 mm Al. Differences among studies may be attributed to variations in methodology, such as radiographic techniques, film-to-focus distance, and measurement procedures.[1,14,33-35] Theracal PT exhibited a radiopacity value similar to that of permanent enamel, whereas Theracal LC showed a lower value than enamel. The other tested calcium silicate-based materials were more radiopaque than permanent enamel. In agreement with the findings, Uslu et al[1] also reported that Theracal PT had



Q1 **Figure 1. Representative radiograph showing all tested dental material groups, the aluminum step wedge, and the sections of the tooth.**

similar radiopacity to permanent enamel, while Theracal LC was less radiopaque. They concluded that Theracal PT may not provide sufficient radiopacity to serve as a base material. According to the results of the study, both Theracal PT and Theracal LC showed radiopacity values lower than that of primary enamel as well. This characteristic may lead to misinterpretation of secondary caries adjacent to the restorative material in treatments involving primary teeth.

Base and liner materials should possess slightly higher radiopacity than enamel to allow clear distinction from carious tissue and ensure visibility of the tooth-restoration interface.[10] However, excessively radiopaque materials may create diagnostic challenges. While this can aid in detection, it may also lead to visual artifacts such as the Mach Band effect.[11] The MTA-based materials, such as Bio-C Repair and NeoPutty MTA, demonstrated the highest radiopacity values in this study. These materials may exhibit the Mach Band effect, creating false radiolucent areas near highly radiopaque regions.

In the present study, Bio-C Repair and NeoPutty MTA showed the highest radiopacity values, and their results were similar to each other. While several factors influence the radiopacity of dental materials, the composition appears to be the most decisive.[36] NeoPutty MTA contains radiopaque tantalum oxide (tantalite), although the manufacturer does not disclose the exact concentration. Since the tested MTA-based materials contained different radiopacifying agents, further studies are warranted to clarify their effects.

According to ISO 9917, glass ionomer-based dental materials should exhibit a radiopacity equal to or greater than 1 mm A.[30] Based on this criterion, Amalgomer and Zirconomer did not meet the ISO 9917 standard. Both materials showed lower radiopacity values than the dentin of both primary and permanent teeth. Due to their low radiopacity, these materials may be radiographically indistinguishable from carious tissue. Although the manufacturers report that both products are radiopaque, the discrepancy may be related to differences in the volume or distribution of radiopaque fillers within the material. While conventional glass ionomer cements are often associated with radiolucency, newer formulations have been developed to improve this property.[36] Among the tested materials, Ionofil U—a conventional glass ionomer—showed lower radiopacity than primary dentin but higher than permanent dentin. Materials with radiopacity lower than enamel can cause diagnostic confusion, as they may be mistaken for carious lesions, pulp tissue, or voids on radiographs.[10] Glass Liner, another tested glass ionomer-based material, also exhibited lower radiopacity than both primary and permanent enamel.

In the present study, the radiopacity value of Riva SC was found to be 6.02 ± 0.15 mm Al, which is lower than the value reported by Lachowski et al[10] (6.65 ± 0.42 mm Al). Nevertheless, Riva SC exhibited a higher radiopacity than enamel both in the current study and in the study conducted by Lachowski et al.

This study has certain limitations. As an in vitro investigation, it does not fully replicate the intraoral environment, including factors such as fluid infiltration. Additionally, the image quality of phosphor plates may degrade over time with repeated use. Variations in radiopacity values reported across different studies may be attributed to differences in radiographic parameters such as current, voltage, exposure time, X-ray source, object-to-source distance, and the specifications of the step wedges used.

Within the limitations of this in vitro study, significant differences were observed in the radiopacity values of the tested dental materials. Ionofil U, Glass Liner, Theracal LC, Calcimol LC, Amalgomer, and Zirconomer exhibited lower radiopacity than both primary and permanent enamel. Amalgomer and Zirconomer showed radiopacity values below that of both primary and permanent dentin, and thus failed to meet the ISO 9917 standard. Conversely, NeoPutty MTA, Bio-C Repair, Endocem MTA, and MTA Repair HP demonstrated higher radiopacity than enamel. While ISO guidelines provide minimum thresholds for radiopacity, no upper limits are currently defined. As dental materials continue to evolve through reformulation, further research evaluating their radiographic performance is warranted.

The findings of this study highlight the importance of considering the radiopacity properties of various materials used in restorative and pediatric dental clinical applications. The use of dental materials with insufficient radiopacity in vital pulp treatments may lead to diagnostic errors when detecting caries or assessing restoration deficiencies. Materials used in both primary and permanent teeth should provide adequate radiopacity to allow clear radiographic differentiation from surrounding structures. Considering the large number of dental materials with different radiopacity values, clinicians should be careful in selecting the appropriate material.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Ethics Committee Approval: Ethical committee approval was received from the Ethics Committee of the University of Necmettin Erbakan (Approval no: 2024/522; Date: 26/12/2024).

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