Radiopacity of different resin-based and conventional luting cements compared to human and bovine teeth

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This study evaluated the radiopacity of different resin-based luting materials and compared the results to human and bovine dental hard tissues. Disc specimens (N=130, n=10 per group) (diameter: 6 mm, thickness: 1 mm) were prepared from 10 resin-based and 3 conventional luting cements. Human canine dentin (n=10), bovine enamel (n=10), bovine dentin (n=10) and Aluminium (Al) step wedge were used as references. The optical density values of each material were measured using a transmission densitometer. Al step wedge thickness and optical density values were plotted and equivalent Al thickness values were determined for radiopacity measurements of each material. The radiopacity values of conventional cements and two resin luting materials (Rely X Unicem and Variolink II), were significantly higher than that of bovine enamel that could be preferred for restorations cemented on enamel. Since all examined resin-based luting materials showed radiopacity values equivalent to or greater than that of human and bovine dentin, they could be considered suitable for the restorations cemented on dentin.

Keywords: Adhesion, Luting cement, Optical density, Radiopacity, Resin cement

INTRODUCTION

All-ceramic restorations are becoming increasingly popular in dentistry due to their outstanding esthetics and high strength⁴¹. Especially for minimal invasive all-ceramic restorations such as inlays, onlays, laminates, adhesive cementation is a prerequisite. Resin-based luting materials considerably increase the resistance of all-ceramic restorations under occlusal loading⁵-⁶. Resin-bonding also reduces microleakage compared to conventional cements⁷.

In particular for esthetic anterior restorations, translucent ceramic materials are preferred where the choice of luting agent has a substantial influence on the outcome⁸. Expanded kits of resin cements with multiple shades are available deriving their shades and opacity from various fillers⁹-¹⁰. The color stability and thereby radiopacity of resin-based luting materials is also of great importance. Among many variables that affect the color stability of resin-based restorative materials or luting-agents, radiopaque fillers play a significant role¹⁰-¹². While the amine accelerator necessary for dual polymerization may also cause color change of the luting agent over time¹³, photo-polymerizing resin-based luting materials are preferred due to their color stability¹⁴-¹⁵. Non-metallic inlays, onlays, all-ceramic crowns and fixed dental prosthesis (FDP) are typically cemented using dual polymerized resin cements¹⁶. On the other hand, chemically polymerizing resin cements are advised for the cementation of prefabricated posts, radiolucent non-metallic posts, carbon-fiber posts, gold inlay/onlay restorations, metallic crowns and FDPs¹⁷-¹⁸.

Radiopacity is an important feature of esthetic resin-based luting materials¹⁸-¹⁹. It is essential that such materials be sufficiently radiopaque to permit detection of marginal overhangs, open gingival margins, as well as recurrent caries in the gingival areas¹⁸,²⁰,²¹. When the luting agent is not radiopaque enough, it is impossible to detect excess luting agent or caries radiographically²⁰. Ideally, restorative materials should have radiopacity values equivalent to or greater than that of dentin²²-²⁵. Previous studies used different methods to evaluate the radiopacity of dental materials²⁶-³⁰. In fact, the International Organization for Standardization (ISO) has published radiopacity evaluation protocol and set guidelines for radiopacity of polymer-based filling, restorative and luting materials³¹. According to the protocol, the radiopacity of a dental material is expressed as optical density value or in terms of equivalent aluminium (Al) thickness (in millimeters) using a reference calibration curve under controlled radiographic conditions³². Consequently, such materials should have radiopacity level equal to or greater than that of Al³².

Filler type and amount of radiopaque fillers may influence the radiopacity of resin-based materials³³. Although filler type does not affect the degree of conversion and polymerization shrinkage of resin composites, the radiopaque particles increase the thermal expansion, hydrolyze the silane bonding agent, and cause opacity³⁴. Quartz and silica fillers on the other hand are not radiopaque. Therefore, it can be anticipated that cements containing such fillers would present less radiopacity compared to those of conventional cements. Some of these resin cements are available in different shades. Since primarily the composition of the cements remains the same, no significant difference could be expected between different shades. Radiopacity level of conventional or resin-based cements may influence the...
The detection of caries or the evaluation of integrity of the restoration margins. From a clinically and biological standpoint, radiopacity level of cements in relation to dentin and enamel could influence choice of cements for tooth-colored indirect restorations.

The purpose of this study was to evaluate the radiopacity of different resin-based luting materials, conventional cements and compare the values to those of human and bovine dental hard tissues and Al step wedge, as the control. The hypothesis tested were that a) resin-based luting cements containing glass particles would show similar radiopacity values, b) resin cements would present less radiopacity compared to conventional cements, and c) different shades of resin cements would show similar radiopacity values.

**MATERIALS AND METHODS**

**Specimen preparation**

Disc specimens (N=130, n=10 per group) (diameter: 6 mm, thickness: 1 mm) were prepared from 10 resin-based and 3 conventional luting cements. The thickness of the specimens were set to 1 mm in accordance with the ISO Standard 404931. The materials, their chemical compositions, manufacturers and batch numbers are listed in Table 1.

Cements were mixed according to each manufacturer’s instructions and compressed between two glass slides in the mold during photo-polymerization (Hilux Ledmax 1040, Darphie Ltd., Bangkok, Thailand). All materials were polymerized for 40 s from a constant distance of 2 mm from the surface. Light output was minimum 500 mW/cm² measured with a radiometer (Hilux Ledmax 1040) after every 10 specimens.

All specimens were ground finished to 400-grit silicon carbide paper (Struers, Willich, Germany) under water to create flat surfaces. Thickness of the specimens was measured with a digital caliper (Youfound Precision Co. Ltd, Zhejiang, China) with a critical tolerance of ±0.01 mm. All specimens were ultrasonically cleaned in distilled water for 5 min (Eurosonic 4D, Euronda S.p.A., Vicenza, Italy). All specimens were then kept in distilled water at 37°C for 24 h. Samples of human canine dentin (n=10), bovine dentin (n=10), bovine enamel (n=10) were

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**Table 1**  Brands, shades, manufacturers, chemical compositions of the materials investigated in this study

<table>
<thead>
<tr>
<th>Brands and shades</th>
<th>Chemical composition**</th>
<th>Batch number</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panavia F TC (PFT)</td>
<td>Paste A: 10-MDP, hydrophobic and hydrophilic dimethacrylate, benzoyl peroxide, camphoroquinone, colloidal silica&lt;br&gt;Paste B: Sodium fluoride, hydrophobic and hydrophilic dimethacrylate, diethanol-p-toluidine, T-isopropylbenzenic sodium sulfinate, barium glass, titanium dioxide, colloidal silica</td>
<td>Paste A: 00222A&lt;br&gt;Paste B: 00122</td>
<td>Kuraray Medical Inc., Okayama, Japan</td>
</tr>
<tr>
<td>Variolink II Universal dual-polymerized (VLD)</td>
<td>Base: Bis-GMA, UDMA, TEGDMA, benzoyl peroxide, Ba-Al- Flurosilicate glass, stabilizers, pigments&lt;br&gt;Catalyst: Ytterbium trifluoride, dimethacrylates, inorganic fillers, Bis-GMA, dl-camphorquinone, stabilizers, pigments&lt;br&gt;Base: monomer 26.3 wt%, filler 73.4 wt%&lt;br&gt;Catalyst high viscosity: monomer 22 wt%, filler 77.2 wt%</td>
<td>Batch no: 58561</td>
<td>Ivoclar Vivadent AG, Schaan, Liechtenstein</td>
</tr>
<tr>
<td>Variolink II Universal Photo-polymerized (VLL)</td>
<td>Base: monomer 26.3 wt%, filler 73.4 wt%&lt;br&gt;Catalyst high viscosity: monomer 22 wt%, filler 77.2 wt%</td>
<td>Batch no: 58561</td>
<td>Ivoclar Vivadent AG, Schaan, Liechtenstein</td>
</tr>
<tr>
<td>Nexus 2 (NXS)</td>
<td>Bis-GMA, 70 wt%, 47 wt % inorganic filler, average particle size: 0.6 µm</td>
<td>Batch no: 403996&lt;br&gt;Catalyst: 406257</td>
<td>Kerr Corp., Orange, CA</td>
</tr>
<tr>
<td>Duolink (DL)</td>
<td>Bis-GMA (5–30 wt%), TEGDMA (5–20 wt%), UDMA (5–15 wt%, base only), glass filler (50–80 wt%)</td>
<td>Batch no: 0400003526</td>
<td>Bisco Inc, Schaumburg, IL</td>
</tr>
<tr>
<td>Brands and shades</td>
<td>Chemical composition**, Batch number</td>
<td>Manufacturer</td>
<td></td>
</tr>
<tr>
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<tr>
<td>Rely X Unicem Aplicap A2 (RX2)</td>
<td>Powder: Silanized glass powder 85–95 wt%, silane treated silica 5–10 wt%, calcium hydroxide 1–5 wt%, substituted pyrimidine 1–5 wt%, sodium persulfate &lt;1 wt%&lt;br&gt; Liquid: Methacrylated phosphoric acid esters 40–50 wt%, TEGDMA 25–35 wt%, substituted dimethacrylate 22–34 wt%&lt;br&gt;Batch no: 258548</td>
<td>3M ESPE AG, Seefeld, Germany</td>
<td></td>
</tr>
<tr>
<td>Rely X Unicem Aplicap A3 (RX3)</td>
<td>Powder: Silanized glass powder 85–95 wt%, silane treated silica 5–10 wt%, calcium hydroxide 1–5 wt%, substituted pyrimidine 1–5 wt%, sodium sulfate &lt;1 wt%&lt;br&gt; Liquid: Methacrylated phosphoric acid esters 40–50 wt%, TEGDMA 25–35 wt%, substituted dimethacrylate 22–34 wt%&lt;br&gt;Batch no: 258548</td>
<td>3M ESPE AG, Seefeld, Germany</td>
<td></td>
</tr>
<tr>
<td>Rely X Unicem Aplicap Translucent (RXT)</td>
<td>Powder: Silanized glass powder 85–95 wt%, silane treated silica 5–10 wt%, calcium hydroxide 1–5 wt%, substituted pyrimidine 1–5 wt%, sodium sulfate &lt;1 wt%&lt;br&gt; Liquid: Methacrylated phosphoric acid esters 40–50 wt%, TEGDMA 25–35 wt%, substituted dimethacrylate 22–34 wt%&lt;br&gt;Batch no: 258548</td>
<td>3M ESPE AG, Seefeld, Germany</td>
<td></td>
</tr>
<tr>
<td>Rely X ARC, Universal A3 (RAC3)</td>
<td>Paste A: Silane-treated silica, TEGDMA, Bis-GMA, functionalized dimethacrylate polymer&lt;br&gt;Paste B: Silane-treated ceramic, TEGDMA, Bis-GMA, silane treated silica, functionalized dimethacrylate polymer&lt;br&gt;Batch no: FLGH</td>
<td>3M ESPE AG, Seefeld, Germany</td>
<td></td>
</tr>
<tr>
<td>Rely X ARC, Transparent A1 (RAC1)</td>
<td>Paste A: Silane-treated silica, TEGDMA, Bis-GMA, functionalized dimethacrylate polymer&lt;br&gt;Paste B: Silane-treated ceramic, TEGDMA, Bis-GMA, silane treated silica, functionalized dimethacrylate polymer&lt;br&gt;Batch no: EYGH</td>
<td>3M ESPE AG, Seefeld, Germany</td>
<td></td>
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<tr>
<td>Ketac Cem Easymix glass ionomer luting cement (KCE)</td>
<td>Powder: Glass powder, polycarboxylic acid, pigments&lt;br&gt; Liquid: Water, tartaric acid, conservation agents&lt;br&gt; Batch no: Powders: 241231&lt;br&gt; Liquid: 235634</td>
<td>3M ESPE AG, Seefeld, Germany</td>
<td></td>
</tr>
<tr>
<td>Adhesor Carbofine Zinc polycarboxylate cement (ZNC)</td>
<td>Powder: Oxides (Zn, Mg, Al), boric acid&lt;br&gt; Liquid: Acrylic acid, maleic acid anhydride, distilled water&lt;br&gt; Batch no: Powders: 1726657&lt;br&gt; Liquid: 1700128</td>
<td>Spofa Dental a.s., Prague, Czech Republic</td>
<td></td>
</tr>
<tr>
<td>Adhesor Zinc phosphate cement (ZNP)</td>
<td>Liquid: “Normal” aqueous solution of phosphoric acid and aluminium orthophosphate and “Rapid” aqueous solution of phosphoric acid, aluminium orthophosphate and zinc orthophosphate&lt;br&gt; Batch no: Powders: 1399466&lt;br&gt; Liquid: 1382770-2</td>
<td>Spofa Dental a.s., Prague, Czech Republic</td>
<td></td>
</tr>
</tbody>
</table>

*MDP: 10-Methacryloyloxydecyl dihydrogen phosphate; TEGDMA: Triethyleneglycol dimethacrylate; Bis-GMA: bisphenol-A-diglycidyl methacrylate; UDMA: urethane dimethacrylate; HEMA: 2-Hydroxyethyl methacrylate. **All information is obtained from material safety sheet data of the products tested.
used as reference of radiopacity, whereas an Al step wedge was used to internal control of radiopacity. Ten enamel and dentin disk specimens were prepared from mandibular bovine incisors (diameter: 6 mm, thickness: 1 mm) by longitudinal sectioning of the buccal side of the teeth after separating the roots. Longitudinal sections of human dentin were also prepared to the same thickness using a micro-slicing device (Accutom, Struers Co, Copenhagen, Denmark).

Radiopacity analysis

An Al step wedge was machined from a single Al block (Alu-Keil, PEHA Medikal Geräte GmbH, Sulzbach, Germany) using electrical discharge machining technique. The maximum thickness of the step wedge was 8 mm where each step had a thickness of 1 mm, length of 4 mm, and width of 14 mm. The Al step wedge was used to internal control of radiopacity.

One specimen of each material, bovine enamel, bovine dentin and human dentin and an Al step wedge were positioned side by side on occlusal D speed radiographic film (Kodak Ultra-speed, Eastman Kodak Company, Rochester, NY) (Fig. 1). A special holder was mounted to ensure a fixed focus/film distance. The films were exposed for 0.38 s with a dental X-ray system (Trophy, Vincennes, France) at 70 kV and 8 mA where the object-to-film distance was 30 cm. All films were processed immediately in a standard automatic processor (Velopex Ready Mixed Developer and Fixer, Hexagon International Ltd, Berkhamsted, UK) (Fig. 2). The optical densities of the radiographic images were measured with a transmission densitometer (Pehamed Denso-Dent Densitometer, PEHA Medikal Geräte GmbH, Sulzbach, Germany). Means of at least 3 readings per specimen was measured with an aperture size of 3 mm (DIN 6868/55). Following the method previously described elsewhere23, a graph were plotted to illustrate the relationship between the step wedge thickness and optical density values with the following equation: \[ y = -0.5296 \ln(x) + 2.1971 \]. From that graph, optical density values of the specimens were used to determine the equivalent Al thickness (eq Al) values (Fig. 3).

Statistical analysis

Statistical analysis was performed using SPSS 13.0 for Windows (SPSS Inc., Chicago, IL). Data were analyzed using one-way analysis of variance (ANOVA), Kruskal-Wallis and Student-Newman-Keuls multiple range tests (\( \alpha = 0.05 \)).

RESULTS

Significant difference was observed between radiopacity values of the tested materials (Kruskal-Wallis) (\( p < 0.0001 \)) (Table 2). Among conventional cements, zinc phosphate cement showed the highest radiopacity (\( p < 0.0001 \)) (7.845±1.011) followed by zinc polycarboxylate (6.290±0.379) and glass-ionomer (1.808±0.258). From
conventional cements only zinc phosphate and zinc polycarboxylate showed significantly higher radiopacity compared to bovine enamel (1.808±0.262). All conventional cements tested showed significantly higher radiopacity than those of human dentin (1.254±0.220) and bovine dentin (1.358±0.174) (p<0.0001) both of which were not significant (p>0.05).

All resin based luting materials (1.441±0.178–4.371±0.410) showed similar to or significantly higher radiopacity values than those of human and bovine dentin.

The radiopacity values of resin luting materials Rely X Unicem (2.102–2.245) and Variolink II (4.072–4.371) were significantly higher than that of bovine enamel (1.808±0.262) being also significant from each other.

**DISCUSSION**

Radiopacity of a material can be simply defined as the inverse of the optical density of a radiographic image. Optical density value is a logarithmic measure of the ratio of the transmitted-to-incident light through the film image, measured by the transmission densitometry. Optical density values depend not only on the inherent X-ray absorption properties of the materials, but also on the characteristics of the film (fog and base density), its exposure parameters, and processing conditions. Therefore, in this study, the equivalent Al thickness values were also calculated in order to compare the results with a reference material. In this study, the results were also compared to human dentin, bovine enamel and bovine dentin. Bovine enamel and dentin were used as it was reported to present similar morphological and histological properties compared to human teeth. Bovine teeth also permitted to make disc-shaped enamel specimens of 1 mm in thickness and 6 mm in diameter that was technically not possible with the human teeth. Since the aperture of the transmission densitometer was 3 mm in diameter, it allowed for the measurement of an area of 7 mm². For this reason, disks with a diameter of 6 mm were obtained from the enamel of bovine mandibular incisor which was not possible in human enamel.

Table 2  Means and standard deviations (SD) of optical density and equivalent Aluminium (Al) step wedge thickness values of the tested materials, human dentin (HD), bovine dentin (BD) and bovine enamel (BE) and statistical differences between groups. See Table 1 for material coding.

<table>
<thead>
<tr>
<th>Material code</th>
<th>Optical density values (Mean±SD)</th>
<th>Equivalent Al Step wedge values (Mean±SD)</th>
<th>Statistical differences*</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD</td>
<td>2.084±0.086</td>
<td>1.254±0.220</td>
<td>A</td>
</tr>
<tr>
<td>BD</td>
<td>2.039±0.067</td>
<td>1.358±0.174</td>
<td>A,B</td>
</tr>
<tr>
<td>PFT</td>
<td>2.007±0.062</td>
<td>1.441±0.178</td>
<td>B,C</td>
</tr>
<tr>
<td>DL</td>
<td>1.999±0.078</td>
<td>1.469±0.235</td>
<td>C</td>
</tr>
<tr>
<td>NXS</td>
<td>1.925±0.081</td>
<td>1.690±0.279</td>
<td>D</td>
</tr>
<tr>
<td>RAC3</td>
<td>1.910±0.071</td>
<td>1.734±0.248</td>
<td>D</td>
</tr>
<tr>
<td>RAC1</td>
<td>1.898±0.065</td>
<td>1.772±0.233</td>
<td>D</td>
</tr>
<tr>
<td>BE</td>
<td>1.888±0.072</td>
<td>1.808±0.262</td>
<td>D</td>
</tr>
<tr>
<td>KCE</td>
<td>1.888±0.071</td>
<td>1.808±0.258</td>
<td>D</td>
</tr>
<tr>
<td>RX2</td>
<td>1.806±0.052</td>
<td>2.102±0.208</td>
<td>E</td>
</tr>
<tr>
<td>RX3</td>
<td>1.788±0.061</td>
<td>2.178±0.259</td>
<td>E</td>
</tr>
<tr>
<td>RXT</td>
<td>1.773±0.068</td>
<td>2.245±0.305</td>
<td>E</td>
</tr>
<tr>
<td>VLD</td>
<td>1.457±0.065</td>
<td>4.072±0.502</td>
<td>F</td>
</tr>
<tr>
<td>VLL</td>
<td>1.418±0.048</td>
<td>4.371±0.410</td>
<td>F</td>
</tr>
<tr>
<td>ZNC</td>
<td>1.224±0.031</td>
<td>6.290±0.379</td>
<td>G</td>
</tr>
<tr>
<td>ZNP</td>
<td>1.110±0.067</td>
<td>7.845±1.011</td>
<td>H</td>
</tr>
</tbody>
</table>

*The same letters in the column indicate no significant differences according to Student-Newman-Keuls multiple range tests (p<0.05).
significant differences. Therefore the first hypothesis could be rejected. All materials had radiopacity values equivalent to or greater than that of human and bovine dentin. Since significant differences in mean radiopacity values were observed between the conventional and resin-based luting materials, the second hypothesis was accepted. On the other hand, as anticipated, cements of the same kind with different shades did not show significant differences yielding to acceptance of the third hypothesis.

The radiopacity values were compared to bovine dentin and human dentin both of which did not show significant differences from one another indicating that bovine dentin could substitute human dentin with its similar morphological and histological characteristics. Variability in radiopacity values reported in different studies could be attributed to many factors. Resin composites are typically composed of inorganic fillers dispersed in a resin matrix. The radiopacity of a resin-based material depends in part on selection of the polymer matrix, chemical nature of the filler particles, their size, density and amount in the resin matrix. While resin matrices such as bisphenol-A-glycidyl methacrylate (Bis-GMA), urethane dimethacrylate (UDMA), 10-methacryloyloxydecyl dihydrogen phosphate (MDP), triethyleneglycol dimethacrylate (TEGDMA), 2-hydroxymethyl methacrylate (HEMA) contribute little to the radiopacity of the material, it is typically the inorganic filler component that contributes most to the radiopacity of resin-based luting materials. However, the findings of this study clearly indicate that both MDP and HEMA could have influenced radiopacity values as the inorganic filler types were similar in these resin cements. The effect of the matrix type on the radiopacity of resin cements requires further investigations.

In resin-based materials, barium, yttrium, ytterbium, zinc, aluminium, strontium, and zirconium are additives that increase radiopacity. Among the tested resin cements, dual-polymerized and photo-polymerized Variolink II presented radiopacity values significantly higher than that of bovine enamel. Both of these cements showed similar radiopacity which could be attributed to the composition of the catalyst that gives the radiopacity to both dual and photo-polymerized cements. The filler content (ytterbium trifluoride) was also similar in these two cements possibly being responsible from similar radiopacity values obtained. As expected, different shades of self-adhesive cement, Rely X Unicem and Rely X ARC, also did not show significant differences in the shade obtained from oxides, which probably did not interfere with the overall radiopacity. Although the filler content was higher than that of Variolink II, radiopacity was significantly lower than those of Variolink II dual and photo-polymerized cements. The difference could be due to the high content of glass particles (85–95 wt%) in Rely X Unicem according to the manufacturer’s information. When conventional cements are compared, the higher radiopacity of zinc polycarboxylate and zinc phosphate more than glass-ionomer could be explained with the magnesium oxide and to glass ionomer, fluoroaluminosilicate glass and barium filler particles, contributing to the radiopacity.

Although radiolucent resin-based luting agents may have optical advantages, the overlaps may not be controlled properly and recurrent decay may not be detected. Their use should be particularly contraindicated in situations where the margins are located in areas that have difficult access. In an in-vitro study, excess cement could not be detected in association with radiopaque resin composite inlays, even with the most radiopaque materials, but they could be detected easier adjacent to radiolucent porcelain inlays. The use of radiopaque resin-based luting materials is therefore especially important in combination with radiolucent restorations such as ceramic laminate veneers, inlays, onlays and fiber posts or in restorations with subgingivally located margins. Although, post-cementation protocols do not presently include routine radiographic examination, inaccurate removal of cement excess may lead to periodontal problems. Particularly when cement film thickness is less than 25–50 μm after cementation, it is favourable to use the highest radiopaque cement possible in order to be detected easily in the radiographs.

Radiographic density is directly obtained from digital image analysis. The pixels already available in grey shades provide the values straight at a scale of 0 to 255 through the sofware. For this reason, direct or indirect digital image analysis is considered as a fast and easy resource for interpreting radiographic density of the restorative materials in dental practice. The advantages of direct digital systems are immediate image capture, lack of processing chemicals and high sensitivity to radiation exposure. Although direct or indirect digital dental radiology systems are preferred to study the radiopacity of a material due to low irradiation dose, instant image, image manipulation, the X-ray film technique is widely used by researchers and manufacturers and it is still considered as a golden standard technique. Hence, the choice between direct and indirect digital image analysis and transmission densitometry requires further investigations.

Variation in radiopacity measurements of the same restorative materials among different studies depends on a number of factors, including speed of the X-ray film, exposure time, voltage used and the age of the developing and fixing solutions. Furthermore, source-film distance, intensifying screens, grids and specimen thickness are also among factors that affect the radiopacity values. Among resin cements, although the radiopacity of Variolink II was the highest in this study and in previous studies, the equivalent Al values were different. While Rubo and El-Mowafy used 2.5 mm thick specimens with focus-object distance of 35 cm at 60 kV. Tsuge used 2.3 mm thick specimens and focus-object distance of 35 cm at 60 kV. In this study, object-to-film distance was 30 cm at 70 kV. ISO standards require the minimum radiopacity of restorative materials be equal
to or greater than that of an equivalent thickness of Al\textsuperscript{31}. Although the radiopacity of dentin and enamel specimens varies, pure Al provides a constant reference value\textsuperscript{32}. In this present study, all materials had greater equivalent thickness of Al, indicating that they all fulfilled the ISO requirements.

One limitation of this study was that the oral environment was not simulated. In the oral environment factors such as oral fluids, soft tissues and the surrounding dental structures may affect the radiopacity levels of restorative materials in that low density restorative materials become more visible on a radiograph when the soft tissue and hard dental structures are superimposed. Furthermore, leakage of ions from silicone, barium, strontium, and sodium filler particles into the aqueous medium may result in reduced radiopacity\textsuperscript{40}. Future studies are warranted to study the radiopacity of luting cements after aging.

CONCLUSIONS

All examined resin-based luting materials showed radiopacity values equivalent to or greater than that of human and bovine dentin but not necessarily higher than that of bovine enamel. Due to the higher radiopacity values of conventional cements and Rely X Unicem and Variolink II resin cements than that of bovine enamel, they could be preferred for restorations cemented on conventional cements and Rely X Unicem and Variolink II resin cements than that of bovine enamel, they could be preferred for restorations cemented on enamel. Since all examined resin-based luting materials showed radiopacity values equivalent to or greater than that of human and bovine dentin, they could be considered suitable for the restorations cemented on dentin.

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