Measuring the Radiopacity of Luting Cements, Dowels, and Core Build-up Materials with a Digital Radiography System Using a CCD Sensor

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Purpose: **This study assessed the radiopacity of five luting cements, five dowels, and five core build-up materials using two target distances.**

Materials and Methods: **Materials were analyzed using a modified version of ISO protocol 4049. samples 1 mm thick were digitally radiographed alongside a stepwedge of aluminum alloy 1100 using a Trophy RVG-4 CCD sensor and 70 kVp X-ray generator. The gray-scale values of the stepwedge and sample were converted to X-ray absorbencies. The relationship between X-ray absorbance and aluminum thickness was linear for thicknesses less than 10 mm and followed a power-law relationship above 10 mm. These relations were used to convert the absorbencies of the samples into aluminum thicknesses. The radiopacity data was subjected to ANOVA/Student–Newman–Keuls testing.**

Results: **All materials were more radiopaque than equivalent thicknesses of aluminum. Each product category contained a wide range of radiopacities. Syringe-dispensed materials tended to be less radiopaque than materials dispensed by mechanically assisted syringe or mixed by hand ($p < 0.01$). Target distance did not affect the measured radiopacity so long as the exposure time was suitably adjusted ($p = 0.86$).**

Conclusions: **All luting cements and core materials met or exceeded the ISO minimums. The tested metal-reinforced glass ionomer core build-up materials were extremely radiopaque. Some publications suggest that excessively radiopaque core materials can hinder a clinician's ability to spot voids or marginal defects.**

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A TRADITIONAL dowel and core restoration involves four main materials: the crown, the core material that supports the crown, the dowel that the core material is attached to, and the luting cement that attaches the dowel to the tooth. In order for these materials to appear on a radiograph, they must be radiopaque. Radiographs are useful not only for evaluating the placement of the restoration, but also for monitoring its long-term stability. Core materials should be radiopaque so they can be inspected for voids and marginal defects. Dental dowels must be radiopaque so clinicians can detect their presence and respond appropriately should re-treatment be necessary. Insurance companies also prefer radiopaque dowels so placement of the dowel can be verified. Luting cements should be radiopaque so a clinician can differentiate the luting cement from secondary decay.

The ISO has published a radiopacity protocol and guidelines for polymer-based filling, restorative, and luting materials.[1] These materials should have a radiopacity equal to or greater than that of aluminum. Aluminum was chosen as a reference

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because its radiopacity has been reported to be similar to dentin[2-4] and it can be easily and accurately machined. Neither the ISO nor the ANSI/ADA has issued radiopacity guidelines for dental dowels.

The standard procedure for determining radiopacity involves radiographing a sample of known thickness next to an aluminum stepwedge reference on D speed film. The optical density of the sample is then compared to that of the stepwedge to determine the equivalent radiopacity per thickness of material. The many advantages of digital radiography have led to the recent creation of an all-digital technique for determining radiopacity.[5] This technique was reported to be insensitive to the initial choice of target distance (focus to detector); however, because of the small sample size used in that study, this effect cannot be conclusively ruled out.

The purpose of this study was to confirm the lack of effect due to target distance. This required evaluating the radiopacity of five luting cements, five dowels, and five core build-up materials at two target distances.

Materials and Methods

A recently published digital[5] technique for measuring radiopacity was selected for this study. Minor alterations to the technique were made in order to analyze dowels and highly radiopaque materials.

Sample Preparation

Five core build-up materials, five luting cements, and five endodontic dowels were used in this study. Ten specimens of each material were analyzed.

Of the five core build-up materials analyzed in this study, three were resin-based, and two were metal-reinforced, glass-ionomer-based. Of the resin-based materials, Ti-Core® Auto E (Essential Dental Systems, South Hackensack, NJ) was dispensed by a syringe, LuxaCore® Automix Dual (DMG/Zenith, Englewood, NJ) was dispensed by a mechanically assisted syringe, and Ti-Core® Natural (Essential Dental Systems) was mixed by hand. Of the metal-reinforced, glass-ionomer-based materials, Ketac(TM) Silver Aplicap(TM) (3M ESPE, Seefeld, Germany) was dispensed by a mechanically assisted syringe, and Miracle Mix® (GC Co., Tokyo, Japan) was mixed by hand.

Of the five luting cements analyzed in this study, one was a zinc phosphate cement (Henry Schein, Melville, NY), two were self-adhesive resin based cements [syringe-dispensed Embrace(TM) WetBond(TM) (PulpDent, Watertown, MA) and mechanically assisted, syringe-dispensed RelyX(TM) Unicem Aplicap(TM) (3M ESPE)], and two were regular resin-based cements [syringe-dispensed Flexi-Flow Auto(TM) E (Essential Dental Systems), and hand-mixed Flexi-Flow® Natural (Essential Dental Systems)].

Of the five dowels analyzed in this study, two were active metal dowels, and three were passive fiber dowels. The metal dowels were Titanium Flexi-dowel® (Essential Dental Systems) and Stainless Steel Flexi-dowel®. The passive fiber dowels were FibreKor® (Pentron Clinical Technologies LLC, Wallingford, CT), Paradowel® Fiber White (Coltène/Whaledent Inc., Mahwah, NJ), and Snowdowel® (Danville Materials, San Ramon, CA).

The luting cements and core materials were prepared according to their manufacturer's instructions. Immediately after mixing, they were placed into wells created by clipping 1 mm thick plates of aluminum alloy 1100 (Alcoa, Pittsburgh, PA) containing a 4 mm diameter hole on top of glass microscope slides. After the wells were filled, glass slides were clipped on top of the aluminum plates, covering the samples and helping them to achieve a 1 mm thickness.

The endodontic dowels were analyzed as is. All dowels had a shaft diameter of 1 mm, except for Paradowel, which had a diameter of 1.14 mm.

Radiography

Each specimen was then digitally imaged alongside an aluminum stepwedge used as a reference. The stepwedge was fabricated by riveting together 15 1-mm thick sheets of aluminum alloy 1100 (Alcoa). The strips were 10-mm wide, and their lengths ranged from 30 mm at the base of the wedge to 15 mm at the top. The images were taken using a single RVG-4 sensor (Trophy Radiology, Inc. Marietta, GA) and a dental X-ray machine (AcuRay 071A; Belmont, Somerset, NJ) operating at 70 kVp and 10 mA, with a total filtration equivalent to 2.25 mm of aluminum. The RVG sensor has a single ISO value ("film speed") which cannot be changed, and the sensor records for the full exposure time. Two roentgenograms were taken of each luting cement sample and of each core material sample: one at a target distance of 30 cm and another at a target distance of 15 cm. The dowels were only radiographed at a target distance of 30 cm. The exposure time depended on the target distance and radiopacity of the sample. If the measured radiopacity of the sample was less than 8 mm of aluminum alloy 1100, the exposure time was 6/60 (0.10) of a second for the 30 cm target distance and 3/60 (0.05) of a second for the 15 cm target distance. For larger radiopacities, the exposure time was 39/60 (0.65) of a second for the 30 cm target distance and 19/60 (0.32)

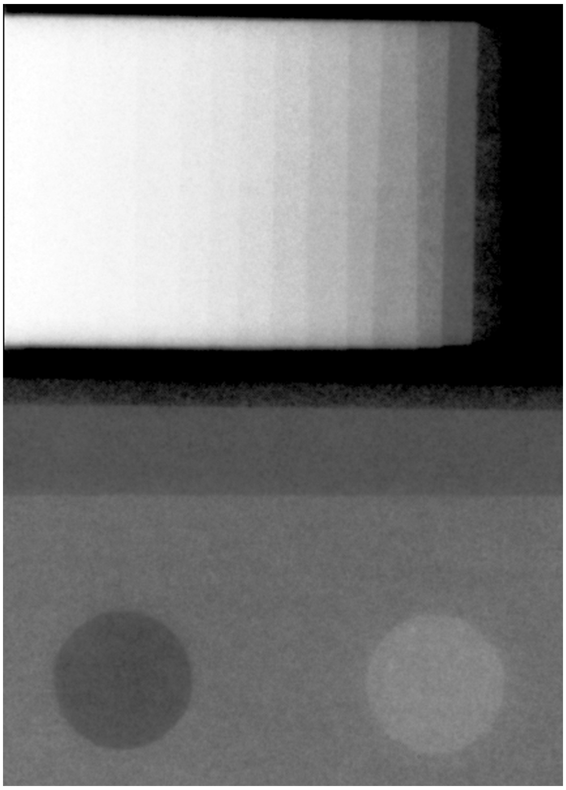

Figure 1. Representative radiograph of Ti-Core Natural taken using an exposure time of 6/60 (0.10) of a second and a target distance of 30 cm.

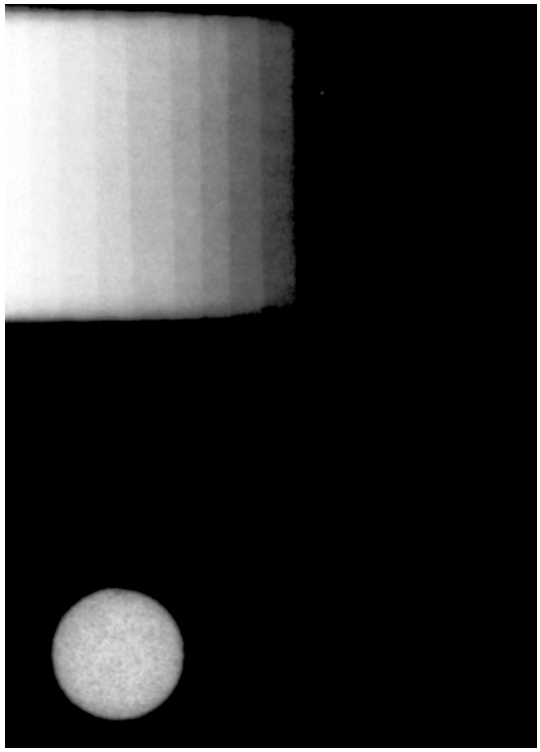

Figure 2. Representative radiograph of Miracle Mix taken using an exposure time of 39/60 (0.65) of a second and a target distance of 30 cm. Steps 1 to 7 of the stepwedge as well as the glass slides and aluminum washer are not visible due to overexposure.

of a second for the 15 cm target distance. The longer exposure times used to image very radiopaque materials produced overexposed radiographs, but helped to provide optimum contrast among the objects of interest (Figs 1 and 2).

Image Analysis

The untreated images were analyzed with open-source graphics software (Gimp 2.0). The histogram tool was used to determine the average gray-scale value—0 (black) to 255 (white) — of the region of the radiographs containing the sample. For the dowel samples, only the center of the dowel shaft, where the dowel's thickness was known to be 1 mm (1.14 mm for Paradowel), was measured. Care was taken to analyze only those regions that were free of air bubbles and other anomalies. The gray-scale value corresponds to the attenuation of the material. This value was converted into an absorbance by using the following formula:

$$A = -\log_{10}(T) = -\log_{10}\left(1 - \frac{G}{255}\right),$$

where A is the absorbance, T is the transmittance, and G is the gray-scale value of the item. This theoretical equation is the same one used in the NIH Image program (developed at the U.S. National Institutes of Health and available on the Internet at http://rsb.info.nih.gov/nih-image/).

From each set of radiographs taken at one of the four target distance/exposure time combinations, ten roentgenograms were chosen at random. In every radiograph, the histogram tool was applied to the regions containing the aluminum stepwedge. The data for each exposure time were converted to absorbencies and plotted against the number of aluminum steps. The plots were then regressed, and the regressions were used to correlate absorbance with aluminum thickness. These correlations were used to convert the previously recorded samples' absorbencies into thicknesses of aluminum.

The 10 radiographs previously chosen for target distance/exposure time combinations of 15 cm, 3/60 (0.05) of a second and 30 cm, 6/60 (0.10) of a second were also analyzed to determine the absorbance of the two glass slides. The mean radiopacities of the slides

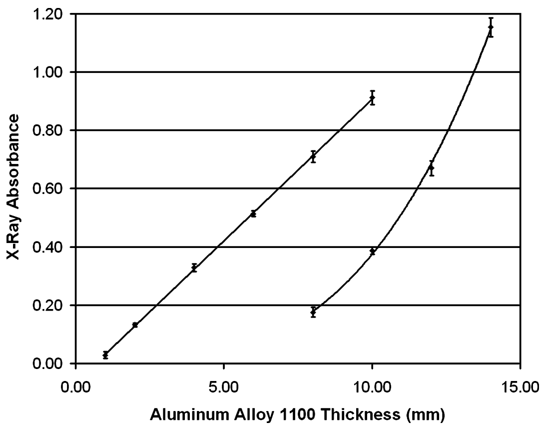

Figure 3. Mean and standard deviation of the absorbencies of the aluminum alloy 1100 stepwedge at a 30 cm target distance. The data with the linear best-fitting curve was taken from images exposed for 6/60 (0.10) of a second. The data that are fit to a power-law curve were taken from images exposed for 39/60 (0.65) of a second.

were subtracted from the luting cement and core build-up data taken at the corresponding target distance in order to find the opacity of those materials.

All the radiopacity data reported in this article are in terms of millimeters of aluminum alloy 1100 per millimeter of material.

Statistical Methods

The radiopacities at the two target distances were compared using two-way ANOVA. The Student–Newman–Keuls (SNK) multiple comparison procedure was used to determine which levels of a factor differed from each other. Results were considered significant if $p < 0.05$.

Results

The absorbance of the aluminum stepwedge at a target distance of 30 cm is plotted in Figure 3. The plot also depicts the two-parameter best-fitting equations for the data. The data from images exposed for 6/60 second followed a linear trend. The data from images exposed for 39/60 second appeared to follow a power-law trend in the range of 8 to 14 mm of aluminum alloy 1100. The power law trend was chosen based upon the empirical data and simple 2 constant nature of the trend equation, $a \cdot x^b$, not because of any theoretical consideration. The data taken at a target distance of 15 cm were remarkably similar to the 30 cm data. For both target distances, the equations of the best-fitting curves and their associated errors are given in Table 1. All regression residuals appeared to be random and showed no correlation with respect to radiopacity; thus, the regressions worked well over their entire range of application.

The mean radiopacity of the two glass slides that covered the samples was 1.79 ± 0.11 mm of aluminum alloy 1100 at a target distance of 15 cm and 1.80 ± 0.06 mm Al at a target distance of 30 cm.

The radiopacity of the materials is given in Tables 2–4. There was no statistical difference ($p = 0.86$) between the radiopacities recorded at the 15 and 30 cm target distances. In order to ascertain the probability of a type II error, a 95% confidence interval for the difference between the two distances was calculated. This interval was −0.08 to 0.07 mm Al 1100. Because the interval is much smaller than the radiopacity measurements

Table 1. Regressions and Errors of the Regressions

Conditions	*Regression Equation*	*Parameter Best-Fits ± Standard Error*	R^2	*Average Magnitude of the Mean Residuals (mm of Aluminum Alloy 1100)*
30 cm, 6/60 second	$a \cdot x + b$	$a = (9.734 \pm 0.060) \times 10^{-2}$ $b = (-6.520 \pm 0.366) \times 10^{-2}$	0.9978	0.04
15 cm, 3/60 second	$a \cdot x + b$	$a = (9.836 \pm 0.089) \times 10^{-2}$ $b = (-9.104 \pm 0.589) \times 10^{-2}$	0.9961	0.06
30 cm, 39/60 second	$a \cdot x^b$	$a = (1.692 \pm 0.211) \times 10^{-4}$ $b = 3.343 \pm 0.048$	0.9955	0.06
15 cm, 19/60 second	$a \cdot x^b$	$a = (1.130 \pm 0.272) \times 10^{-4}$ $b = 3.500 \pm 0.093$	0.9853	0.09

Average magnitude of the mean residuals refers to the average absolute value of the difference between the mean experimental data and the best-fitting regression, an indication of the systematic error involved in using the regressions.

Table 2. Equivalent Radiopacities and Theoretical Appearance of the Core Materials

	Radiopacity (mm Al 1100/mm material)		*Theoretical Opacity*	
Material	*30 cm Target Distance*	*15 cm Target Distance*	*2 mm Sample*	*4 mm Sample*
Ti-Core Auto E	1.0 ± 0.1	1.0 ± 0.1		
Ti-Core Natural	1.9 ± 0.2	1.9 ± 0.1		
LuxaCore Automix Dual	2.3 ± 0.1	2.2 ± 0.1		
Miracle Mix	9.2 ± 0.7	9.2 ± 0.7		
Ketac Silver Aplicap	10.5 ± 0.3	10.4 ± 0.3		

All materials were statistically different. Theoretical appearance is based upon the listed data when the exposure time is adjusted to produce an infinitesimal background fog on the Trophy RVG-4/Belmont AcuRay 071A system.

and even smaller than the standard deviation of the measurements, it is unlikely that a type II error occurred.

The radiopacities of syringe-dispensed materials were statistically lower ($p < 0.01$) than mechanically assisted, syringe-dispensed or hand-mixed materials.

Discussion

From a theoretical standpoint, long target distances are suggested to help ensure that the X-ray sensor or film is uniformly irradiated; however, the target distance must be easily reproducible to ensure that all radiographs are consistently exposed. A convenient way to ensure this is to use the X-ray head cone as a guide and to place the sample to be analyzed right at the end of, or just inside of, the cone. Most spacer cones create a target distance of 20 to 30 cm. The results of this article show that target distances of 15 and 30 cm produce similar radiopacity values with similar precision.

The glass slides that covered the core material and luting cement samples had a radiopacity of almost 1 mm of dentin per slide. Because this radiopacity is not negligible, the measurements may be affected by "beam hardening," the process by which low-energy X-rays are preferentially absorbed by a material, leaving only the more penetrating high-energy X-rays to reach the deeper layers of the material. Beam hardening also occurs when the thickness of material analyzed is not negligible. Theoretically, this process influences the measured radiopacity by a small amount.[5] In clinical situations, the materials that cover the luting cement, dowel, or core material, such as bone, dentin, or a restorative crown, harden the X-ray beam. One could argue that the radiopacity provided by the slides helps to mimic the clinical situation. One could also argue that using radiopaque slides is merely equivalent to use of an X-ray generator with greater inherent filtration.

Table 3. Equivalent Radiopacities and Theoretical Appearance of the Luting Cements

	Radiopacity (mm Al 1100/mm material)		*Theoretical Opacity*	
Material	*30 cm Target Distance*	*15 cm Target Distance*	*0.2 mm Sample*	*0.4 mm Sample*
Embrace WetBond	1.2 ± 0.1	1.3 ± 0.1		
Flexi-Flow Auto E	1.6 ± 0.1	1.6 ± 0.1		
Flexi-Flow Natural	1.9 ± 0.1	1.9 ± 0.1		
RelyX Unicem Aplicap	2.7 ± 0.1	2.7 ± 0.1		
Zinc Phosphate Cement	4.6 ± 0.3	4.7 ± 0.2		

All materials were statistically different. Theoretical appearance is based upon the listed data when the exposure time is adjusted to produce an infinitesimal background fog on the Trophy RVG-4/Belmont AcuRay 071A system.

Table 4. Equivalent Radiopacities and Theoretical Appearance of the Endodontic dowels

Material	*Radiopacity (mm Al 1100/mm material)*	*Theoretical Opacity*	
		0.8 mm Sample	*1.2 mm Sample*
FibreKor	1.0 ± 0.1		
Paradowel	1.1 ± 0.1		
Snowdowel	1.7 ± 0.2		
Titanium flexi-dowel	4.9 ± 0.2		
Stainless steel flexi-dowel	9.9 ± 0.3		


All materials were statistically different except for FibreKor and Paradowel. Theoretical appearance is based upon the listed data when the exposure time is adjusted to produce an infinitesimal background fog on the Trophy RVG-4/Belmont AcuRay 071A system.

The concept of equivalent radiopacity assumes that materials are macroscopically homogenous radiologically. On a microscopic scale, materials such as glass ionomer cements and composite resins are composed of several discrete materials, each with different radiopacities. Macroscopically, however, these materials are homogenous. Most fiber dowels are composite systems that are not macroscopically homogenous; the radiopacity of the fibers is different from that of the resin matrix. Nevertheless, within the resolution of the X-ray sensor system used in this article, all materials, including fiber dowels, appeared homogenous.

The relative radiopacities listed in Tables 2–4 are all expected, given the compositions of the materials. The X-ray attenuation of an element is roughly proportional to its atomic number raised to the third power.[6] Heavy elements such as barium and silver absorb roughly 10 times as many X-rays per unit mass as light elements like carbon and oxygen.[7] Therefore, dental materials that contain a large amount of heavy elements, such as metallic dowels, metal-reinforced glass ionomer cements, and zinc phosphate cement, are expected to be very radiopaque. Highly filled polymer composites, such as LuxaCore Automix Dual, contain radiolucent resin and a large amount of fillers, such as heavy metals or metal salts. These composites are usually very viscous and require mechanical assistance to be properly mixed. This may explain why syringe-dispensed resin composites like Embrace WetBond and Flexi-Flow Auto are relatively radiolucent.

The relative radiopacities listed in Tables 2–4 agree reasonably well with previously published values. The dowel data compares moderately well to the results of a study conducted by Finger et al; 4.9 versus 4.3 mm Al for titanium dowels, 1.7 versus 1.1 for Snowdowel, and 1.0 versus 0.8 for FibreKor.[8] The luting cement data compares favorably with previous work; 4.6 versus 6.5 mm Al for zinc phosphate cement[9,10] and 1.2 to 2.7 versus 1.1 to 2.4 for resin-based luting cements.[10] Finally, the core materials also performed similarly to previously reported values: 10.5 versus 10.0 mm Al for Ketac Silver[11] and 1.0 to 2.3 versus 1.0 to 3.0 for resin-based core materials.[12] Because the studies used for comparison are several years old, one would expect that some variations in radiopacity could occur if manufacturers have updated their product formulations.

The equivalent radiopacities reported in this article are for luting cements and core materials cured at room temperature in the absence of water. Usually, this is a good approximation of the clinical condition; however, it has been reported that a metal-reinforced glass ionomer cement, Ketac Silver (similar to Miracle Mix), will occupy a volume 8.7% larger if cured for 14 days at body temperature in distilled water rather than in a waterless environment (silicone oil).[13] A hybrid resin-modified glass-ionomer cement, Fuji II LC Core (similar to RelyX Unicem), was 7.4% by volume larger after 14 days in water rather than in silicone oil.[13] Because the cement cured in water is less dense, its radiopacity per unit thickness (equivalent radiopacity) will be smaller. Thus, the clinical radiopacities of the glass ionomer materials should be smaller than the values reported in this article. On the other hand, a resin-based material, Ti-Core (similar to Flexi-Flow, LuxaCore, and Embrace), was reported to be only 0.5%

larger in water vs. silicone oil after 14 days at body temperature.[13] Therefore, the clinical radiopacity of these materials should be close to the values reported in this article.

All of the luting cements tested in this study exceeded the ISO requirement. The ISO does not adequately explain the rationale behind their radiopacity requirement for polymer-based luting materials. Usually only a thin layer of luting cement is used. Therefore, the relative contribution of the cement compared with the much thicker dowel is negligible,[14] as seen in Tables 3 and 4. As a result, the radiopacity of a luting cement is usually a minor concern compared with its clinical performance. Nevertheless, radiopacity is a desirable property that can help a clinician verify cement placement and identify secondary decay, especially in oval-shaped canals that require thicker layers of luting cement.

All the core materials tested in this study met or exceeded the ISO equivalent radiopacity requirement for polymer-based restorative materials — 1 mm of aluminum. A radiopaque core material allows a clinician to radiographically inspect the core material for voids. Several studies have shown that this is best accomplished in materials whose equivalent radiopacity is roughly equal to enamel's.[3,15–17] Thus, detecting voids in highly radiopaque materials, such as Miracle Mix and Ketac Silver, might be difficult.[15] Evidence of this can be seen in Table 2. A 2-mm thick bubble in a 4-mm thick slab of metal-reinforced glass ionomer core material would barely be identifiable.

Neither the ISO nor the ANSI/ADA has issued radiopacity guidelines for dental dowels; however, dowels must be radiopaque enough to alert clinicians to their presence. One peer-reviewed study indicated that the minimum clinically acceptable equivalent radiopacity is about 1 mm of aluminum.[8] All the dowels tested in this study met or exceeded this guideline. The radiopacity of various dowels has also been evaluated by the Clinical Research Associates (CRA) Newsletter.[18] They claimed that the radiopacity of FibreKor dowels was "fair," Paradowel and Snow dowel were "good," and titanium or stainless steel dowels were "excellent." Our data indicated that the radiopacities of these dowels are 1.0, 1.1, 1.7, 4.9 and 9.9 mm of aluminum alloy 1100 per mm of dowel material, respectively.

Sabbagh and others reported that the radiopacity of an object on traditional D speed film can differ by roughly 10% from that of the object on a phosphor plate.[19] This is a reasonable observation considering the two systems use different techniques to measure X-ray radiation. Therefore, it is quite possible that the digital sensor used in this study produces radiopacity values that may differ from those measured on traditional film. Because clinical use of film radiography is declining as digital systems are adopted, future work on radiopacity should concern itself with modern imaging systems. The Trophy RVG-4 sensor used in this experiment is similar to most commercial digital intraoral sensors in that it uses a scintillation screen to convert incident X-rays into less energetic radiation that is then detected by another sensor such as a CCD or CMOS. Thus, the results of this experiment are expected to be applicable to most digital sensor systems other than phosphor plates; however, as of now, there is no experimental evidence to support this generalization.

Conclusions

The radiopacity of five luting cements, five core materials, and five dowels were measured at two target distances. The following conclusions were drawn:

1. Both the means and standard deviations of the measured radiopacities were independent of the target distance used, as long as the exposure time was suitably adjusted.
2. All materials appeared to be satisfactorily radiopaque and homogenous.
3. Syringe-dispensed materials tended to be less radiopaque than mechanically assisted syringe-dispensed or hand-mixed materials.
4. The tested metal-reinforced, glass ionomer core build-up materials were extremely radiopaque. Some publications suggest that excessively radiopaque core materials can hinder a clinician's ability to spot voids or marginal defects.

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