Radiopacity of endodontic materials using two models for conversion to millimeters of aluminum

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Abstract: The aims of the present study were to compare conventional radiography, radiographs digitized with a scanner or photographic camera, and digital radiography, used to evaluate the radiopacity of endodontic materials, and to compare the accuracy of linear and quadratic models used to convert radiopacity values to equivalent millimeters of aluminum (mm Al). Specimens of AH Plus, Endofill, Biodentine and BioMTA materials (n = 8) were radiographed next to an aluminum step-wedge using radiographic films and digital radiography systems (FONA CMOS sensor, Kodak CMOS sensor and photosensitive phosphor plate-PSP). Conventional radiographs were digitized using a scanner or photographic digital camera. Digital images of all the radiographic systems were evaluated using dedicated software. Optical density units (ODU) of the specimens and the aluminum step-wedge were evaluated by a photo-densitometer (PTDM), used in conventional radiographs. The radiopacity in equivalent mm Al of the materials was determined by linear and quadratic models, and the coefficients of determination (R^2) values were calculated for each model. Radiopacity of the materials ranged from -9% to 25% for digital systems and digitized radiographs, compared to the PTDM ($p < 0.05$). The R^2 values of the quadratic model were higher than those of the linear model. In conclusion, the FONA CMOS sensor showed the lowest radiopacity variability of the methodologies used, compared with the PTDM, except for the BioMTA group (higher than PTDM). The quadratic model showed higher R^2 values than the linear model, thus indicating better accuracy and possible adoption to evaluate the radiopacity of endodontic materials.

Keywords: Dental Cements; Radiography, Dental, Digital; Endodontics; Materials Testing; Radiology.

Introduction

The radiopacity of endodontic cements should be sufficient to differentiate them from dentine and cortical bone (American National Standards Institute and American Dental Association #57 - ANSI/ADA),[1] in determining the quality of a root canal filling.[2] The standards set by both the International Organization for Standardization 6876 – ISO[3] and ANSI/ADA[1] recommend the following procedure to quantify the radiopacity of endodontic cements. The specimens must be prepared on standardized discs and radiographed next to a step-wedge that has a purity of at least 98% aluminum, using conventional radiographic film. Both standards recommend that the radiopacity should be evaluated with a photo-densitometer (PTDM). According to both ANSI/ADA[1] and ISO[3] standards, the endodontic cement must have a radiopacity equivalent to at least 3 millimeters of aluminum (mm Al).

Currently, the radiopacity of dental materials is evaluated using digitized images of conventional radiographs – indirect technique,[4,5] or by digital radiography – direct technique.[6,7,8,9] In the indirect technique, the conventional radiographic images are converted to a digital signal by a high-resolution scanner[10,5] or digital camera.[2,11,12] The direct technique uses digital sensors charge-coupled devices (CCD)[13] or complementary metal oxide semiconductors (CMOS),[14] or else photosensitive phosphor plates (PSP).[15]

Although studies have evaluated the radiopacity of endodontic cements using conventional digitized radiographs or digital radiographs, there is no consensus on how digital images influence the radiopacity of endodontic materials. Barium-containing materials tend to be 13% more radiopaque in radiographs taken by the CCD sensor than in conventional film.[13] On the other hand, other endodontic materials were 7% to 20% less radiopaque in PSP images than in conventional film.[6] These variations can be critical in evaluating cements that have a radiopacity close to 3 mm Al, such as Biodentine.[14,16]

To the best of our knowledge, there are no studies that have compared the radiopacity of endodontic materials using conventional radiography evaluated with a PTDM [recommended by ISO[3] and ANSI/ADA[1]], indirect methods of conventional film digitization (scanner and camera), or a CMOS digital sensor.

In conventional radiographs, a PTDM must be used to determine the value of optical density units (ODU equivalent to absorbance) of materials and of the aluminum step-wedge.[6] In digital radiographs and images, dedicated software (*e.g.* ImageJ or Adobe Photoshop) is used to obtain the grayscale values.[14,17] Comparison of the different systems to evaluate the radiopacity of materials requires the data of the aluminum step-wedge and the specimens to be presented in absorbance or grayscale values. To this end, the absorbance values are converted to grayscale or vice versa using a logarithmic equation.[13] The next step is to obtain the radiopacity values of materials in mm Al. In most studies, a linear model is applied,[11,16] but other models may also be used, such as the quadratic model.[7] It is important to note that it is not necessary to convert the grayscale values of an aluminum step-wedge, or those of specimens to absorbance scale, when only digital systems are used to evaluate radiopacity. Only the equation to convert grayscale to an equivalent aluminum thickness of specimens has to be used.[4,11,16]

In a linear model there is a linear relationship between the dependent variable (output) and the independent variable (input). A linear relationship implies that the independent variable is always of the first order (first power), *i.e.*, the dependent variable and independent variable are related by a constant rate of change. On the other hand, in a polynomial model, there is a curvilinear relationship between the dependent and the independent variables. A curvilinear relationship implies that the order of the independent variable is greater than that of the first power; in other words, the rate of change between the dependent variable and the independent variable is not constant. The simplest case of the polynomial model is the second-order or quadratic model.[18] Although there are studies in the literature using both linear and quadratic models to obtain the radiopacity values of materials in mm Al, it is not known how they influence the radiopacity results of endodontic materials.

The aims of the present study were: a) to compare conventional radiography, radiography digitized with a scanner or photographic camera, and digital radiography systems, in evaluating endodontic material radiopacity, and b) to compare the accuracy of the linear and quadratic models in converting absorbance and grayscale data of specimens to their corresponding equivalent in mm Al. The null hypothesis is that there is no difference among the systems or the mathematical models in their evaluation of the radiopacity of the endodontic materials used in the present study.

Methodology

Four endodontic materials were used, one containing tricalcium silicate (Biodentine, Septodont, Saint-Maur-des-Fossés, France), one composed of zinc oxide and eugenol (Endofill, Ligas Odontológicas, Catumbi, Brazil), one of epoxy resin (AH Plus, Dentsply Sirona Endodontics, Ballaigues, Switzerland), and one containing calcium carbonate (BioMTA, Intradent, Belém, Brazil). The materials were manipulated according to the manufacturer's instructions. Eight discs of each material, 10 mm in diameter and 1-mm thick, were made in compliance with ISO.[3] The specimens were stored at 37°C and 95% humidity for 24 hours, and then radiographed as shown in Table 1.

Conventional radiography

The samples were placed on top of occlusal radiographic E-speed films, next to an aluminum step-wedge (98.5% Al, 8 steps with 2-mm increments per step). The Focus 50540 X-ray unit (Instrumentarium Dental; Tuusula, Finland) was used to make the radiographic exposure, using the following parameters: 65 kVp, 7 mA, exposure time of 0.25 seconds and a 320-mm source-to-object distance.[7] After automatic processing, the radiographic films were digitized by a scanner (Microtek, Hsinchu City, Taiwan) having 300 DPI resolution, using Microtek ScanWizard 5 (Microtek, Hsinchu City, Taiwan) software,[7] or by a semiprofessional digital camera (Canon, Tokio, Japan) having a 100-mm macro lens, and using the following parameters: lens-to-object distance of 40 cm, ISO 100, shutter aperture of 7.1 and shutter speed of 1/100.

Digital radiography

The samples were placed on top of the following digital sensors: FONA CMOS sensor (CDR Elite, Schick by Sirona Dental Inc., Long Island, USA), KODAK CMOS sensor (6100, Kodak Co., Rochester, USA), or PSP (Digora, Soredex, Nahkelantie, Tuusula, Finland). The radiographic parameters were the same as those of conventional radiography, except for the exposure time, which was 0.16 seconds.[7]

Images evaluation

A PTDM (MRA, Indústria de Equipamentos Eletrônicos, Ribeirão Preto, Brazil) was used to acquire the ODU values from specimens radiographed using conventional films. It was calibrated with a 1-mm aperture and used to measure the optical densities of the materials, the aluminum step-wedge and the unexposed film. The PTDM shoots visible white light on one side of the film and electronically measures the amount of light leaving the opposite side.[19] Each specimen was measured three times to obtain the average. We used the histogram tool of Photoshop CC 2015 for the Windows operative system (Adobe Systems Incorporated, Mountain View, USA) to measure the grayscale of the materials and the aluminum step-wedge in the digital images of all the radiographic systems.

Radiopacity (mm Al) calculation

The radiopacity values obtained by the PTDM for conventional radiographs were used as the gold standard. For this reason, the grayscale values had to be converted to absorbance values using a logarithmic equation to compare the radiopacity of the materials, measured using the digital systems and the conventional radiographs, as follows:[20]

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

where: A is the absorbance value and G is the grayscale value of any pixel of a digital image.

Table 1. Radiographic acquisition methodologies and manufacturers.

Methodology	Manufacturer
Conventional radiography - occlusal radiographic E-speed films (Insight)	Kodak Co., Rochester, USA
FONA CDR Elite CMOS sensor	Schick by Sirona Dental Inc., Long Island, USA
KODAK 6100 CMOS sensor	Kodak Co., Rochester, USA
Photosensitive phosphor plate (Digora)	Soredex, Nahkelantie, Tuusula, Finland
Conventional radiography digitized by Camera EOS T6	Canon, Tokyo, Japan
Conventional radiography digitized by scanner	Microtek ScanMaker i800, Hsinchu City, Taiwan

In addition, since most studies today use digital radiography systems to assess the radiopacity of endodontic materials,[4,14,17] the ODU values of the PTDM were converted to grayscale using the same equation as that applied to compare grayscale values of the PSP, FONA, KODAK, scanner and camera methodologies.

The equivalent radiopacity (mm Al) of each material was determined by using a linear and quadratic model. The linear model described by Húngaro-Duarte et al. is:[11]

$$\frac{A \times 2}{B} + \text{mm Al inmediatly below RDM}$$

where:
A = radiographic density of the material (RDM) – radiographic density of the aluminum step-wedge increments right below RDM;
B = radiographic density of the aluminum step-wedge increments right above RDM – radiographic density of the aluminum step-wedge increments right below RDM;
2 = 2-mm increments of the aluminum step-wedge.

The mathematical solution of this formula was done by hand and revised by two authors to ascertain the results. It is worthwhile mentioning that Húngaro-Duarte et al.[11] consider the grayscale values as RDM.

The quadratic model equation was built using the "fit" function of the MATLAB®2015a, v.8.5 for windows software (The MathWorks, Apple Hill Drive, Natick, US). The "roots" function of the MATLAB provided the values of the quadratic model. The radiopacity equivalent to mm Al corresponded to the lowest value for each material. The procedure was divided into two parts, a quadratic model for the correlation between the grayscale values of the step-wedge and its value in mm Al, and a linear fit for the correlation between the grayscale values of the specimens and its mm Al, based on the previous correlation. The radiopacity values—whose equivalence to mm Al of each material was obtained by converting PTDM-measured ODU/absorbance values—were calculated with a similar procedure. The difference was that the grayscale values were converted to absorbance values by equation 2 above, prior to applying the quadratic model equation. All absorbance/ODU values were converted to grayscale values to make the comparison between models, and the PTDM values were used as the gold standard.

The MATLAB®2015a, v.8.5 (Microsoft Windows 7 Ultimate SP1, CPU: 2.30 GHz, RAM: 4 Gb) was used to perform the algorithms and calculations of coefficients of determination (R^2). The comparisons of the different radiographic systems and of the quadratic and linear models were made by one-way analysis of variance (ANOVA), and Tukey's post-test, using the GraphPad Prism statistical program (GraphPad Software, San Diego, USA), with the significance level set at 5%.

Results

Comparison of aluminum step-wedge mathematical fit models

Table 2 shows the R^2 values obtained from the quadratic and linear models. The R^2 values of the quadratic model were higher than those of the linear model, thus indicating better accuracy of the quadratic fit model.

Table 2. Coefficients of determination (R^2) values of quadratic and linear models for all radiographic methodologies and endodontic materials.

Methodology	Biodentine		BioMTA		AH Plus		Endofill	
	QM	LM	QM	LM	QM	LM	QM	LM
Camera	0.999	0.958	0.993	0.938	0.999	0.963	0.999	0.959
FONA	0.999	0.986	0.999	0.990	0.998	0.984	0.998	0.986
KODAK	0.987	0.976	0.988	0.979	0.989	0.982	0.991	0.986
PSP	0.999	0.992	0.998	0.981	0.999	0.991	0.998	0.984
Scanner	0.999	0.971	0.999	0.967	0.999	0.971	0.999	0.956

QM: Coefficients of determination of the quadratic model; LM: Coefficients of determination of the linear model; PSP: photosensitive phosphor plate; FONA: Fona CMOS sensor; KODAK: Kodak CMOS sensor.

The following comparisons were made between the different methodologies and mathematical models to obtain mm Al and the variability of each cement.

Biodentine

The comparison using both mathematical models in relation to absorbance values showed no significant difference ($p > 0.05$) among the PTDM, FONA and scanner methodologies. The camera, KODAK, and PSP methodologies showed higher radiopacity ($p < 0.05$) than the PTDM; the differences were 15%, 20% and 18%, respectively (Table 3). The comparison in grayscale values (Table 4) showed no significant difference between the PTDM and the other methodologies ($p > 0.05$), except for the KODAK methodology, which showed 14% higher radiopacity ($p < 0.05$).

BioMTA

The comparison in relation to absorbance values showed no significant difference among the methodologies ($p > 0.05$) except for KODAK, which showed the highest radiopacity ($p < 0.05$), i.e. 15% higher radiopacity than PTDM (Table 3). The comparison in grayscale values showed that all the methodologies showed higher radiopacity (about 8% to 25%) than the PTDM methodology ($p < 0.05$) (Table 4).

AH Plus

The comparison in absorbance values showed no significant difference among the PTDM, FONA, and KODAK methodologies ($p > 0.05$). The PSP, scanner and camera methodologies showed higher radiopacity than the PTDM methodology ($p < 0.05$), about 11%, 8% and 6%, respectively (Table 3). The comparison in grayscale values showed that there was no significant difference between the PTDM and the other methodologies ($p > 0.05$) (Table 4).

Endofill

The comparison in absorbance values showed that the KODAK methodology had the highest radiopacity ($p < 0.05$), i.e. about 11% higher, whereas the FONA and scanner methodologies had lower radiopacity than PTDM ($p < 0.05$), *i.e.* about 7% and 14% lower, respectively. No significant difference was found among the PTDM, PSP and camera methodologies ($p > 0.05$) (Table 3). The comparison in grayscale values showed that there was no significant difference between the PTDM and FONA methodologies ($p > 0.05$). The PSP, KODAK, scanner and camera methodologies showed higher radiopacity ($p < 0.05$) than PTDM, i.e. about 17%, 22%, 5% and 9%, respectively (Table 4).

Mathematical model comparison

In general, there was a significant difference between the mathematical models ($p < 0.05$) and the PTDM, and between the linear and quadratic model ($p < 0.05$), as shown in Figure.

Discussion

The present study used different methodologies to obtain absorbance and grayscale values, and, therefore, the radiopacity value. Since each device/methodology presents different parameters that could influence

Table 3. Radiopacity (mean and SD) calculated with the quadratic model in mm Al, comparing grayscale values (converted to absorbance) of the methodologies used with the ODU values of the PTDM.

Methodology	Biodentine	BioMTA	AH Plus	Endofill
PTDM	1.85 (0.27)^{a}	4.09 (0.21)^{a}	10.44 (0.61)^{a}	5.01 (0.28)^{a}
PSP	2.21 (0.22)^{b}	4.12 (0.20)^{a}	11.60 (0.62)^{b}	5.11 (0.35)^{a}
FONA	2.03 (0.12)^{a,b}	4.09 (0.31)^{a}	10.83 (0.54)^{a,c}	4.64 (0.20)^{b}
KODAK	2.13 (0.22)^{b}	4.70 (0.31)^{b}	10.96 (0.58)^{a,c}	5.59 (0.38)^{c}
Scanner	2.06 (0.16)^{a,b}	4.08 (0.23)^{a}	11.35 (0.68)^{b,c}	4.31 (0.31)^{d}
Camera	2.18 (0.18)^{b}	4.20 (0.24)^{a}	11.07 (0.87)^{b,c}	4.87 (0.35)^{a}

mm Al: Millimeters of aluminum; PTDM: photo-densitometer; PSP: photosensitive phosphor plate; FONA: Fona CMOS sensor; KODAK: Kodak CMOS sensor; ODU: optical density units. Different letters in the rows indicate statistically significant differences between methodologies for each material ($p < 0.05$).

Table 4. Radiopacity (mean and SD) calculated with the quadratic model in mm Al, comparing ODU values of the PTDM (converted to grayscale) with the grayscale values of all methodologies used.

Methodology	Biodentine	BioMTA	AH Plus	Endofill
PTDM	2.09 (0.17)^{a,c}	3.76 (0.18)^{a}	11.14 (0.83)^{a}	4.58 (0.26)^{a}
PSP	2.09 (0.27)^{a,c}	4.35 (0.23)^{b}	11.10 (0.52)^{a}	5.41 (0.37)^{b}
FONA	2.13 (0.11)^{a}	4.09 (0.30)^{c}	10.79 (0.54)^{a}	4.61 (0.20)^{a}
KODAK	2.38 (0.19)^{b}	4.72 (0.29)^{d}	10.74 (0.64)^{a}	5.63 (0.36)^{b}
Scanner	1.91 (0.19)^{c}	4.21 (0.24)^{b,c}	11.01 (0.60)^{a}	4.84 (0.32)^{c}
Camera	2.11 (0.20)^{a,c}	4.29 (0.25)^{b}	10.90 (0.80)^{a}	4.99 (0.35)^{c}

mm Al: Millimeters of aluminum; PTDM: photo-densitometer; PSP: photosensitive phosphor plate; FONA: Fona CMOS sensor; KODAK: Kodak CMOS sensor; ODU: optical density units. Different letters in the rows indicate statistically significant differences between methodologies for each material ($p < 0.05$).

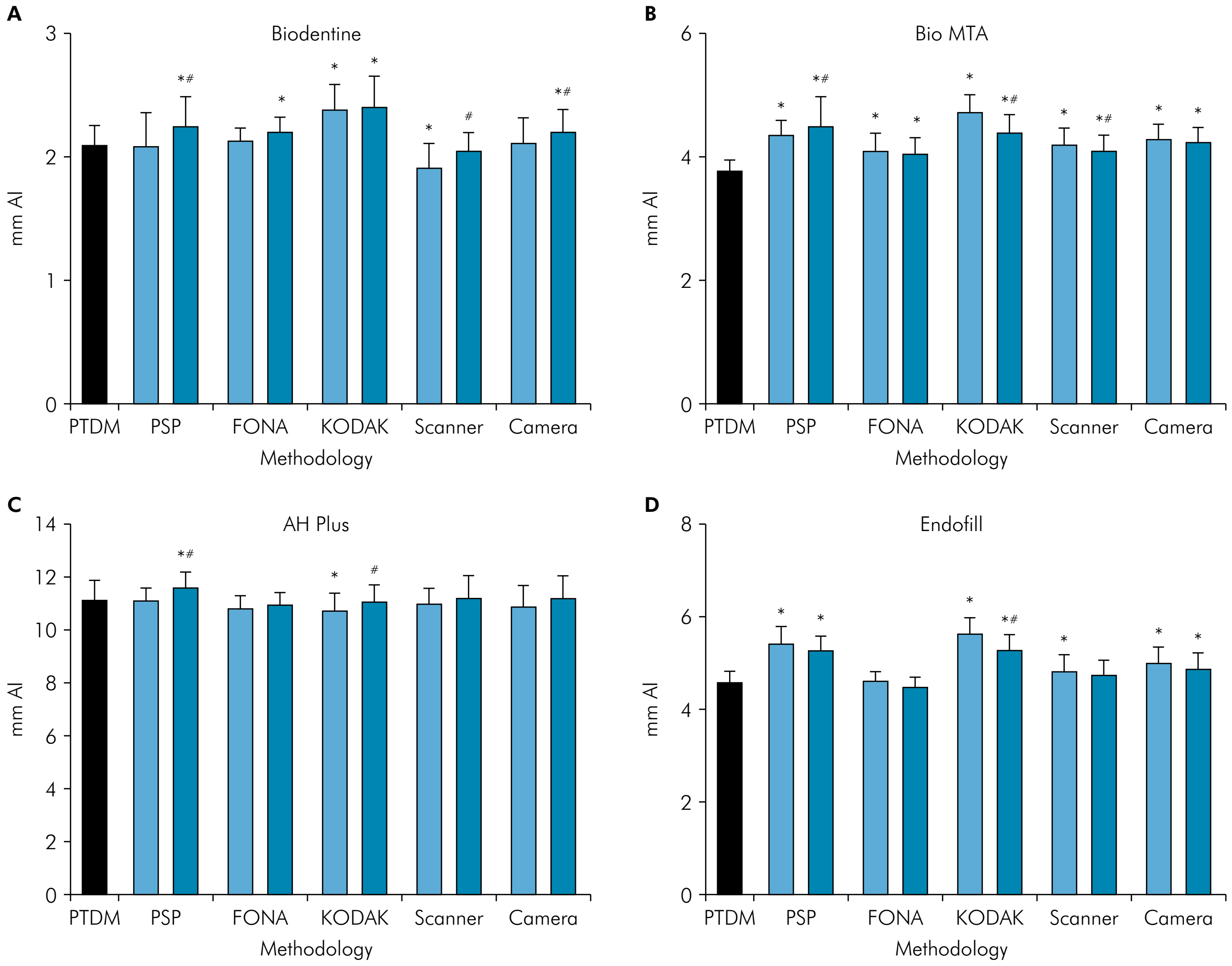

Figure. Mathematical comparison between the quadratic model (light blue) and linear model (blue) for radiopacity (mean and SD). ODU values obtained with the PTDM were converted to grayscale and compared with the grayscale values of the PSP, FONA, KODAK, scanner and camera methodologies. *indicates significant differences between the methodology and PTDM. #indicates significant differences between each mathematical model for each methodology group. Millimeters of Aluminum = mm Al, PTDM = photo-densitometer, PSP = photosensitive phosphor plate, FONA = Fona CMOS sensor, KODAK = Kodak CMOS sensor, ODU = optical density units.

the radiopacity of each cement, contrasting results were expected.[15] The null hypothesis was rejected because the quadratic model presented greater accuracy than the linear model in the conversion of absorbance and grayscale values to mm Al, and there were differences among the methodologies in the radiopacity evaluation of endodontic materials.

In radiological physics, radiographic (or optical) density is defined as the degree of darkening of a film after processing. Mathematically, it is stated as such:

$$RD = -\log_{10}\left(\frac{I}{I_0}\right), \tag{1}$$

where I_0 is the intensity of light incident on the film, and I is the intensity of light transmitted through the film. The quotient I/I_0 is known as the transmittance of the film, whereas I_0/I is known as the opacity of the film.[19,21] In a digital image, the grayscale values (the degree of brightness of the image pixels) oscillate between 0 (black) and 255 (white). The absorbance value (A) in a digital image is stated by the following equation:

$$A = -\log_{10}\left(1 - \frac{G}{255}\right), \tag{2}$$

where G is the grayscale value of any pixel in the image.[20]

Although both radiographic density and absorbance are based on the same equation (mathematically equivalent), they are not conceptually equal. Absorbance is the relative amount of light absorbed by the pixels of a digital image, and radiographic density refers to the relative amount of light traversing sections of a film. Thus, whereas radiographic density is measured with a densitometer,[19] absorbance requires merely knowing the grayscale value, which may be measured directly by an image processing program (*e.g.* ImageJ).

The radiopacity values (mm Al) obtained with the PTDM were considered the gold standard, because they are recommended by ISO.[3] Two different analyses were performed to make the comparison between the ODU and the grayscale values. In the first analysis, the ODU values obtained with the PTDM by conventional radiography were converted to grayscale, and, in the second, all grayscale values obtained in the digital images were converted to absorbance values.

Two models for radiopacity interpretation were used, the linear[11] and the quadratic models, the latter being based on a quadratic/logarithmic fit equation. The quadratic model is critically different from the linear model. First, it is based on a quadratic fit, which showed better results herein than the linear fit in terms of R^2 values for each cement considered. Second, it is better than the linear model particularly for regions where the values of absorbance and step-wedge of mm Al are high, especially in regard to endodontic materials with high absorbance values (*e.g.* AH Plus). Third, it is an automatic and fast method that requires merely knowing the grayscale values of each type of cement and respective aluminum step values for the cement types, and the grayscale values of each type of specimen. Therefore, it can be said that our mathematical model is a generalization of the linear model. The result of the present study corroborates that of the study by Akcay et al.[7] who used the quadratic fit model in luting cements, but contrasts with the study by Gu et al.[20] who recommends the linear model.

The Biodentine radiopacity values were higher using the PSP, the camera and the KODAK CMOS sensor, in terms of absorbance, and also higher using the KODAK CMOS sensor, in terms of grayscale, in comparison with the PTDM. However, these values did not reach the minimum 3 mm Al recommended by ISO.[3] This is consistent with previous studies that have demonstrated the insufficient radiopacity of Biodentine.[14,22] It is important to highlight that there was a tendency for the KODAK CMOS sensor and PSP to show higher or similar radiopacity than the other methods, both in terms of absorbance and grayscale. This observation is consistent with the study by Rasimick et al.[13], which used a different digital sensor (Gendex eHD), and attributed the higher radiopacity to the sensitivity of digital sensors and high-energy photons. In the case of the FONA CMOS digital sensor, overall, it showed values similar to the PTDM, and may be more adequate, because it comes closest to what is recommended by ISO.[3] This difference may be attributed to the characteristics of the KODAK CMOS sensor, whose manufacturer claims that the device sensor has 20 lp/mm resolution,[23] which is higher than the 16.7 lp/mm of the FONA CMOS sensor.[24]

Thus, it can be hypothesized that the KODAK CMOS sensor selectively captures more high-energy photons. This could be explained by studies that have shown that CMOS sensors are more sensitive, and allow a higher perception of low contrast detail.[25]

The radiopacity of the AH Plus was about 11 mm Al, and there was no significant difference among the methodologies, except for PSP and PTDM, when the grayscale values were converted to absorbance values. A previous study[7] also found no differences in the radiopacity of the AH Plus when digitized films, CCD digital sensor and PSP were used, even though the radiopacity found for this material was 7.8 mm Al. It has been reported that the radiopacity of the AH Plus is approximately 7.8 mm Al when measured with the scanner, PSP and digital sensor,[7] 9.8 mm Al, with the scanner,[4] 10.41 mm Al, with the CCD digital sensor[26] and 14 mm Al, with the photodensitometer.[27] The divergent information on AH Plus radiopacity[4,7,27] could be attributed to the use of different devices used and methodologies applied.

All sealers showed similar or higher radiopacity values for PSP than PTDM, for both grayscale and absorbance. This observation contrasts with that of a previous study,[6] which observed lower values for PSP. The difference could be attributed to different parameters used to acquire the radiographic images.

The present study used digitization by scanner and digital cameras to evaluate the radiopacity of certain endodontic materials. In general, except for the absorbance values of Endofill, none of the materials showed any difference for either absorbance or grayscale values evaluated by PTDM, scanner or camera methodologies. Digitation by scanner enables good resolution, radiographic positioning and reproducibility, and requires no zoom adjustment or any source-to-object distance (focal length).[28] However, X-ray scanners are expensive, time-consuming and not as readily available as digital still cameras.[29] Digital cameras require adjusting of the radiographic and zooming distance[28] of the camera; this can cause distortion of the image, depending on the values chosen for the photographic parameters, such as diaphragm aperture, exposition time and sensor sensibility.[29] In addition, radiographic images obtained by the indirect technique tend to exhibit a higher gray level variation, because the variability of grayscale values depends on the specific characteristics of the scanner [30] or photographic camera used.

In summary, the radiopacity variations from -9% to 25% of endodontic materials, found by different radiographic systems and mathematical models may be critical for evaluating materials whose radiopacity is closer to 3 mm Al, thus leading to overestimation or underestimation of radiopacity, and elevating it above or reducing it below the 3 mm Al recommended by ISO.[3]

Conclusion

In conclusion, the FONA CMOS sensor showed the lowest radiopacity variability of the methodologies used, compared with the PTDM, except for the BioMTA group (higher than PTDM).The quadratic model showed higher coefficients of determination (R^2) values in comparison with the linear model, thus indicating better accuracy, and possible adoption to evaluate the radiopacity of endodontic materials.

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