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ORIGINAL ARTICLE

Radiopacity of dental restorative materials

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Abstract
Objectives Radiopacity of dental materials enables clinician to radiographically diagnose secondary caries and marginal defects which are usually located on the proximal gingival margin. The aim of this study was to measure the radiopacity of 33 conventional resin composites, 16 flowable resin composites, and 7 glass ionomer cements and to compare the results with the radiopacity values declared by the manufacturers.
Materials and methods From each restorative material, six 2-mm-thick disk-shaped specimens were fabricated and eight 2-mm-thick sections of teeth were made and used as reference. The material samples and tooth sections were digitally radiographed together with the aluminum stepwedge. Gray values were obtained from the radiographic images and radiopacity values were calculated and statistically analyzed. Post hoc Tukey's honestly significant difference test was used to calculate significant differences in radiopacity values between materials and reference dentin and enamel values.
Results The radiopacity values of all 56 restorative materials were above the dentin reference radiopacity value; however, 4 out of 33 conventional composites and 3 out of 16 flowable resin composites had significantly lower radiopacity than enamel ($p<0.05$). There were up to 1.53 mm eq Al differences between the measured and the manufacturers' declared radiopacity values of some materials.
Conclusions Majority of the materials exceed enamel radiopacity and would not hamper radiographic diagnosis of secondary caries. However, manufacturers' data are not always reliable.
Clinical relevance Materials with radiopacity lower than enamel might be misinterpreted as secondary enamel caries on radiographic images, especially when applied as initial increment on the proximal gingival margin.

Keywords Radiopacity · Dental material · Composite resin · Glass ionomer cement

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Introduction

Radiopaque dental restorative materials enable better radiographic detection of secondary caries [1–3] which is the cause for up to half of all operative dentistry procedures performed on adults [4]. Furthermore, radiopaque materials enable the clinician to evaluate restoration integrity at following recall appointments, to detect voids, overhangs, open margins [5], proper contours, and contacts [6, 7], and even to locate misplaced fragments in the case of traumatic accidents [8] or operative procedures [9]. Therefore, the radiographs have become one of the dentists' primary diagnostic aids in examining their patients. Poorterman et al. [10] reported that clinical examination detects <15 % of inadequate restorations, while the rest are found radiographically. Secondary caries is located on the proximal gingival margin in 80 to 90 % [11], where radiography is often the only way for its detection.

For the abovementioned reasons, the radiopacity of dental restorative materials has been studied regularly. In the recent years, more attention was given to the methodology of radiopacity measurement [12–14] and comparison of digital and conventional radiography [13, 15, 16]. Therefore, the number of restorative materials included in majority of recent studies was relatively low [5, 17–24]. Even though there are some exceptions, most of dental materials examined in these articles are not available on the market anymore. Therefore, dentists have to rely on the data provided by manufacturers.

The aim of this study was to measure the radiopacity of 56 permanent restorative materials which are commonly used on the gingival part of class II restoration and to compare their radiopacity with the radiopacity values declared by the manufacturers. The radiographic images of the specimens were also checked for radiographically visible inhomogeneities in their composition.

Materials and methods

Restorative material and tooth specimen preparation

Different types of restorative materials, which are used as initial increment on the gingival part of class II restoration, were included in this study. The evaluated restorative materials were 33 conventional resin composites (Table 1), 16 flowable resin composites (Table 2), and 7 glass ionomer cements (Table 3). From each restorative material, six 2-mm-thick disk-shaped specimens were fabricated with a cylindrical mold. The mold was made from a 2-mm-thick steel plate with a 10-mm opening placed on a glass plate. After filling the material into the mold, a second glass plate was pressed on top to form a smooth surface. Special attention was paid not to include any air bubbles in the material. The conventional resin composites, flowable resin composites, and resin-modified glass ionomers were polymerized with light-emitting diode curing lamp (Bluephase, Ivoclar Vivadent, Schaan, Liechtenstein; Soft start) for 20 to 40 s according to the manufacturer's instructions. The conventional glass ionomer specimens were removed from the mold after the manufacturer's recommended setting time. All the specimens with visible inhomogeneities were replaced with a new specimen.

To obtain the reference enamel and dentin radiopacity values, two incisors, one canine, two premolars, and three molars were longitudinally sectioned with Isomet saw (Buehler, Düsseldorf, Germany) to obtain eight 2-mm-thick samples. The material and tooth specimen thickness were verified with a digital caliper to be within the 2.00± 0.02 mm limits.

Radiopacity measurements

The sets of six restorative material samples and tooth sections were radiographed with aluminum stepwedge (aluminum alloy EN 1050 containing 99.5 % of Al) which was used as a reference [14]. The stepwedge had four steps, with thickness of 1.00, 2.00, 4.00, and 8.00 mm [12]. The radiographic images were acquired with a storage phosphor plate system (3×4 cm Digora Imaging Plate and Digora FMX scanner; Soredex Corporation, Tuusula, Finland) and a digital X-ray machine (Planmeca Prostyle Intra, Planmeca Oy, Helsinki, Finland) operating at 70 kV and 8 mA with a total filtration equivalent of 2.0 mm of Al. The exposure time was 0.20 s and focus-to-object distance was 40 cm. A 2-mm-thick lead sheet plate was placed under the plate to avoid backscattered radiation. One unexposed plate was scanned in an identical manner to obtain base plus fog density. All exposed plates were scanned immediately after exposure.

Data analysis

The resulting images were transferred as 8-bit Bitmap image files to a personal computer for further analysis with the software program Image J 1.41o (Wayne Rasband, National Institutes of Health, Bethesda, MD, USA). On each image, an area of interest with a size of 10 mm^2 was selected on each step of aluminum stepwedge image and the reference mean gray values were calculated. On the images of the tooth samples, an area of interest with a size of 2 mm^2 for dentin and 1 to 3 mm^2 for enamel was selected and the mean (standard deviation [SD]) gray values were calculated. On the images of material samples, an area of interest with a size of 8 mm^2 was selected on each specimen. Care was taken to analyze only those regions which were free of air bubbles and other anomalies (if they were not present throughout the specimen). Gray values from tooth or material specimens were pooled and the mean (SD) gray value of each material was calculated.

The gray values were then converted into absorbencies using the following formula: $A=-\log_{10}(T)=-\log_{10}(1-G/255)$, where A is the absorbance, T is the transmittance, and G is the gray value [12]. The absorbencies of aluminum stepwedge were plotted against the thickness of aluminum steps and the plots were then linearly regressed to correlate the tooth and material absorbencies with aluminum. The obtained radiopacity values for 2-mm-thick samples were then converted in the radiopacity values for 1 mm of the material or tooth. These radiopacity values (the equivalent thickness of aluminum for 1 mm sample thickness) were then used in statistical analysis.

The materials were divided into three groups, i.e., conventional resin composites, flowable resin composites, and glass ionomer cements. The reference dentin and enamel values were included in these groups for the analysis. Analysis of variance (ANOVA) was used to test if there are statistically significant differences in radiopacity values among the materials ($\alpha=0.05$) in these three groups. Post hoc Tukey's honestly significant difference (HSD) test was used to calculate significant differences in radiopacity values between materials and reference dentin and enamel values in each group ($\alpha=0.05$). The data were analyzed with the software SigmaStat for Windows version 2.03 (Aspire Software International, Ashburn, VA, USA).

The radiographic images of the specimens were also checked for radiographically visible inhomogeneities in

Table 1 Conventional resin composite materials used in the study

Brand name	Shade	Batch	Filler load		Inorganic filler load		Type
			wt%	vol%	wt%	vol%	
Filtek Silorane[a]	A2	8BE	N/A	N/A	76	55	Silorane-based
Filtek Supreme XT[a]	A2D	8BK	N/A	N/A	78.5	59.5	Nano-hybrid
Filtek Supreme XT[a]	A2E	3910A2E	N/A	N/A	78.5	59.5	Nano-hybrid
Miris2[b]	NR	0157743	N/A	N/A	80	65	Nano-hybrid
Miris2[b]	S2	0135732	N/A	N/A	80	65	Nano-hybrid
Synergy D6[b]	Dentin A2/B2	0147957	80	65	N/A	N/A	Nano-hybrid
Synergy D6[b]	Enamel Universal	0152941	80	65	N/A	N/A	Nano-hybrid
Ceram X duo[c]	D2	0469	76	57	N/A	N/A	Nano-hybrid
Ceram X duo[c]	E2	4006	76	57	N/A	N/A	Nano-hybrid
G-ænial[d]	A2	0911171	N/A	N/A	N/A	N/A	Composite
G-ænial[d]	IE	0911171	N/A	N/A	N/A	N/A	Composite
G-ænial[d]	P-A2	0911121	N/A	N/A	N/A	N/A	Composite
Gradia Direct Posterior[d]	P-A2	0709124	77	65	N/A	N/A	Micro-hybrid
Gradia Direct X[d]	X-A2	0704142	77	65	N/A	N/A	Micro-hybrid
Kalore[d]	A2	0903251	82	N/A	N/A	N/A	Nano-hybrid
Venus[e]	A2	010141	N/A	61	N/A	N/A	Micro-hybrid
Artemis[f]	A2 dentin	J05728	N/A	N/A	75–77	55–58	Micro-hybrid
Artemis[f]	A2 enamel	H34120	N/A	N/A	75–77	55–58	Micro-hybrid
IPS Empress Direct[f]	Dentin A2	M14198	83	N/A	60.5	45	Nano-hybrid
IPS Empress Direct[f]	Enamel A2	M13572	77.5–79	N/A	75–79	52–59	Nano-hybrid
Te-Econom[f]	A2	K47739	N/A	N/A	81	62	Micro-hybrid
Te-Econom Plus[f]	A2	K45558	76	60	N/A	N/A	Micro-hybrid
Tetric EvoCeram[f]	A2	K56744	82–83	N/A	75–76	53–55	Nano-hybrid
Premise[g]	Dentine A2	2903955	84	71.2	N/A	N/A	Nano-hybrid
Premise[g]	Enamel A2	07-1067	84	71.2	N/A	N/A	Nano-hybrid
Clearfil AP-X[h]	A2	00966A	86	70	N/A	N/A	Micro-hybrid
Clearfil Majesty Posterior[h]	A2	00010A	92	82	N/A	N/A	Nano-hybrid
Beautifil II[i]	A2	110740	83.3	68.6	N/A	N/A	Nano-hybrid
Amelogen Plus[j]	A2	B372Z	76	61	N/A	N/A	Micro-hybrid
Amelogen Plus[j]	EN	B4L3S	76	61	N/A	N/A	Micro-hybrid
Amaris[k]	O2	0809303	80	N/A	N/A	N/A	Micro-hybrid
Amaris[k]	TN	731771	80	N/A	N/A	N/A	Micro-hybrid
Grandio[k]	A2	0815444	87.0	71.4	N/A	N/A	Nano-hybrid

"Filler load," "Inorganic filler load," and "Type" are as declared by the manufacturer

Manufacturers of materials:

[a] 3M ESPE, St. Paul, MN, USA

[b] Coltène/Whaledent, Altstätten, Switzerland

[c] Dentsply DeTray, Konstanz, Germany

[d] GC Dental Products, Aichi, Japan

[e] Heraeus Kulzer, Hanau, Germany

[f] Ivoclar Vivadent, Schaan, Liechtenstein

[g] Kerr Italia, Salerno, Italy

[h] Kuraray Medical, Okayama, Japan

[i] Shofu, Kyoto, Japan

[j] Ultradent Products, South Jordan, UT, USA

[k] Voco, Cuxhaven, Germany

Table 2 Flowable resin composite materials used in the study

Brand name	Shade	Batch	Filler load		Inorganic filler load		Type
			wt%	vol%	wt%	vol%	
Filtek Supreme XT Flowable[a]	A2	3913A2	N/A	N/A	65	55	Flowable nano-hybrid
Synergy Flow[b]	A2/B2	0140535	N/A	N/A	55	32	Flowable nano-hybrid
X-flow[c]	A2	2824	60	38	N/A	N/A	Flowable
G-ænial flo[d]	A3	1002051	N/A	N/A	N/A	N/A	Flowable
G-ænial flo[d]	AO3	1003011	N/A	N/A	N/A	N/A	Flowable
Gradia Direct Flo[d]	A2	0711051	N/A	N/A	N/A	N/A	Low-viscosity flowable micro-hybrid
Gradia Direct LoFlo[d]	A2	0712121	N/A	N/A	N/A	N/A	High-viscosity flowable micro-hybrid
Venus Flow[e]	A2	010118	N/A	N/A	62	N/A	Flowable micro-hybrid
Te-Econom Flow[f]	A2	K51637	N/A	N/A	62	38	Flowable micro-hybrid
Tetric EvoFlow[f]	A2	L05210	62	N/A	57.5	30.7	Flowable nano-hybrid
Premise Flowable[g]	A2	2888726	72.5	N/A	N/A	N/A	Flowable nano-hybrid
Clearfil Majesty Flow[h]	A2	00204A	81	62	N/A	N/A	Flowable nano-hybrid
Beautifil Flow F02[i]	A2	120718	54.5	34.6	N/A	N/A	Low-viscosity flowable
Beautifil Flow F10[i]	A2	080707	53.8	33.3	N/A	N/A	High-viscosity flowable
PermaFlo[j]	A2	B31TY	68	N/A	N/A	N/A	Flowable micro-hybrid
Grandio Flow[k]	A2	0815448	80.2	65.7	N/A	N/A	Flowable nano-hybrid

"Filler load," "Inorganic filler load," and "Type" are as declared by the manufacturer

Manufacturers of materials:

[a] 3M ESPE, St. Paul, MN, USA

[b] Coltène/Whaledent, Altstätten, Switzerland

[c] Dentsply DeTray, Konstanz, Germany

[d] GC Dental Products, Aichi, Japan

[e] Heraeus Kulzer, Hanau, Germany

[f] Ivoclar Vivadent, Schaan, Liechtenstein

[g] Kerr U.S.A., Orange, CA, USA

[h] Kuraray Medical, Okayama, Japan

[i] Shofu, Kyoto, Japan

[j] Ultradent Products, South Jordan, UT, USA

[k] Voco, Cuxhaven, Germany

their composition. In this visual evaluation, the relative number (descriptively from very rare inclusions, rare inclusions, a number of inclusions to a large number of inclusions), shape (round or irregular), radiopacity/radiolucency, and size (approximate diameter of inclusions in micrometers) of the inclusions in the material specimens were described. The results were presented in the tables together with the radiopacity values declared by manufacturers and visual description of the radiographic images of specimens.

Results

The dentin and enamel reference radiopacity values were 1.03 (0.03) and 1.91 (0.07)mm eq Al, respectively. The ANOVA detected statistically significant differences ($P \leq 0.001$) in the mean values of materials and reference tooth values in all three groups. The power of the performed tests was 1,000 ($\alpha = 0.05$). The results of Tukey's HSD test with the available manufacturer-declared radiopacity values and description of the specimens are presented for conventional resin composites (Table 4), flowable resin composites (Table 5), and glass ionomer cements (Table 6). The radiopacity values of all conventional resin composite materials were above the reference dentin radiopacity value. The radiopacity values of G-ænial A2, G-ænial IE, Gradia Direct Posterior P-A2, and Filtek Silorane A2 were between the dentin and enamel radiopacity values. The radiopacity value of Amaris TN was not statistically significantly different from the reference enamel radiopacity value. The highest mean radiopacity values were measured for the Clearfil Majesty Posterior A2, Beautifil II A2, Amelogen Plus EN, Amelogen Plus A2, Ceram X duo

Table 3 Glass ionomer cement materials used in the study

Brand name	Shade	Batch	Powder–liquid ratio		Type
			Powder (g)	Liquid (g)	
Ketac Molar Quick Aplicap[a]	A2	227967	3.4	1	Conventional
Ketac N100[a]	A2	K3K3	1.3	1.0	Resin-modified
Photac Fil Quick Aplicap[a]	A2	242197	N/A	N/A	Resin-modified
Fuji II LC capsule[b]	A2	0709141	0.33	0.10	Resin-modified
Fuji IX GP Extra[b]	A2	0802254	0.40	0.12	Conventional
GlasIonomer FX-II[c]	A2	100513 (powder) 080507 (liquid)	2.6	1.0	Conventional
Ionofil Molar AC Quick[d]	A2	0827006	N/A	N/A	Conventional

"Powder–liquid ratio" and "Type" are as declared by manufacturer

Manufacturers of materials:

[a]3M ESPE, St. Paul, MN, USA

[b]GC Corporation, Tokyo, Japan

[c]Shofu, Kyoto, Japan

[d]Voco, Cuxhaven, Germany

D2, IPS Empress Direct Dentin A2, Te-Econom Plus A2, Tetric EvoCeram A2, Clearfil AP-X A2, Artemis A2 dentin, and Te-Econom A2, which all exceeded 3 mm eq Al. Among them, the radiopacity of Te-Econom A2 was notably the highest with 4.63 (0.15)mm eq Al.

The radiopacity values of all tested flowable resin composite materials were also above the reference dentin radiopacity value, with the radiopacity of Synergy Flow A2/B2, Gradia Direct LoFlo A2, and Beautifil Flow F10 A2 being between the dentin and enamel radiopacity values. The radiopacity values of Beautifil Flow F02 A2, Te-Econom Flow A2, Filtek Supreme XT Flowable A2, and Gradia Direct Flo A2 were not statistically significantly different from the reference enamel radiopacity value. All other materials were more radiopaque than enamel. The highest radiopacity was reached by Tetric EvoFlow A2 with 2.99 (0.08)mm eq Al.

The radiopacity values of all tested restorative glass ionomer cement materials exceeded both dentin and enamel reference radiopacity values. The radiopacity value of Photac Fil Quick Aplicap A2 was the highest, with 3.15 (0.14) mm eq Al.

Visual examination of the radiographic images (Tables 4, 5, and 6; Fig. 1) revealed that most of the specimens were homogeneous. However, some of the specimens had a large number of inclusions present throughout the material. Materials we described as inhomogeneous are Premise Enamel A2, Premise Dentine A2, Amelogen Plus A2, Ceram X duo D2, Te-Econom A2, G-ænial flo AO3, and G-ænial flo A3.

Discussion

The radiopacity values of all 56 restorative materials were above the dentin reference radiopacity value. However, the measured radiopacity values of 5 out of 33 conventional resin composite materials, 7 out of 16 flowable resin composite materials, and none of 7 restorative glass ionomer materials were significantly lower or similar to the enamel reference radiopacity value.

According to arbitrary ISO 4049 specifications, the radiopacity of restorative materials should be higher than that of the same aluminum thickness [25], which is close to that of human dentin [3, 26]. The aluminum radiopacity is, therefore, a commonly used threshold value by manufacturers when they declare their material to be radiopaque, although no definition of a "radiopaque material" exists [27].

Secondary caries and marginal defects are usually located on the gingival part of class II restoration [11]; therefore, radiography is often the only means of their detection. Materials with radiopacity lower than that of enamel are, therefore, not suitable for use as an initial increment. The initial increment has to be sufficiently radiopaque to make the tooth–restoration margin clearly visible [28]. On the other hand, highly radiopaque materials may mask caries lesion because of superimposition [29]. Nevertheless, in connection with a very radiopaque restoration, the contrast between light and dark areas can be enhanced, making the dark borderline area appear darker. This visual illusion is called the Mach band effect [30]. Espelid et al. discovered that the highest accuracy for radiographic diagnosis of secondary caries is obtained when restorative material has radiopacity slightly greater than that of enamel (i.e., 2 mm eq Al) [31].

The access, adaptation, and adhesion of the restorative material are often inferior on the gingival margin of class II restoration. Therefore, flowable composites were recommended to ease adaptation, decrease occurrence of voids, and reduce microleakage [32–35]. However, some in vitro studies have shown that the use of flowable composites show no apparent advantages over conventional composites [36, 37]. Nevertheless, many dentists have readily accepted flowable composites for a wide variety of uses mainly because of easier application. However, flowable composites are generally less filled and consequently less radiopaque than conventional composites and can, therefore, present diagnostic challenge on radiographs [5]. Similarly, the conventional and resin-modified glass ionomer cements are often used as base materials in the open and closed

Table 4 Radiopacity of 33 conventional resin composite materials with dentine and enamel radiopacity values as reference (mean (SD) equivalent thickness of aluminum for 1 mm sample thickness), with supplementary radiopacity values declared by manufacturers and description of the radiographic images of specimens

Material	Mean (SD) (mm eq Al)	Subset[a]	Radiopacity value declared by the manufacturer	Description of the radiographic images of specimens
Dentine	1.03 (0.03)	a	/	/
G-ænial A2	1.29 (0.05)	b	Radiopaque	Homogeneous
G-ænial IE	1.30 (0.06)	b	Radiopaque	Homogeneous
Gradia Direct Posterior P-A2	1.55 (0.10)	c	Radiopaque	Homogeneous
Filtek Silorane A2	1.64 (0.11)	c	Radiopaque	Homogeneous with rare irregular radiolucent inclusions ~600 μm in diameter
Enamel	1.91 (0.07)	d	/	/
Amaris TN	2.12 (0.11)	d, e	210 % Al	Homogeneous
Amaris O2	2.15 (0.10)	e, f	210 % Al	Homogeneous
Gradia Direct X X-A2	2.35 (0.10)	e, f, g	Radiopaque	Homogeneous
Filtek Supreme XT A2E	2.38 (0.11)	f, g, h	200 % Al	Homogeneous
Miris[2] S2	2.40 (0.12)	g, h	Radiopaque	Homogeneous
Synergy D6 Enamel Universal	2.41 (0.11)	g, h, i	Radiopaque	Homogeneous
Synergy D6 Dentin A2/B2	2.42 (0.12)	g, h, i, j	Radiopaque	Homogeneous with very rare irregular radiolucent inclusions ~400 μm in diameter
Miris2 NR	2.43 (0.09)	g, h, i, j	Radiopaque	Homogeneous
Filtek Supreme XT A2D	2.48 (0.12)	g, h, i, j, k	200 % Al	Homogeneous
Grandio A2	2.58 (0.10)	g, h, i, j, k, l	250 % Al	Homogeneous
Premise Enamel A2	2.61 (0.12)	h, i, j, k, l	282 % Al	Inhomogeneous with large number of irregular radiolucent inclusions ~300 μm in diameter
Artemis A2 enamel	2.62 (0.11)	h, i, j, k, l	200 % Al	Homogeneous
Kalore A2	2.64 (0.10)	i, j, k, l	>250 % Al	Homogeneous
IPS Empress Direct Enamel A2	2.66 (0.13)	j, k, l	200 % Al	Homogeneous
Premise Dentine A2	2.69 (0.12)	k, l, m	282 % Al	Inhomogeneous with large number of irregular radiolucent inclusions ~500 μm in diameter
G-ænial P-A2	2.71 (0.12)	k, l, m	Radiopaque	Homogeneous
Ceram X duo E2	2.80 (0.11)	l, m	200 % Al	Homogeneous with very rare irregular radiolucent inclusions ~500 μm in diameter
Venus A2	2.93 (0.14)	m, n	Radiopaque	Homogeneous
Clearfil Majesty Posterior A2	3.04 (0.12)	n	250 % Al	Homogeneous
Beautifil II A2	3.12 (0.10)	n, o	340 % Al	Homogeneous
Amelogen Plus EN	3.29 (0.12)	o, p	Radiopaque	Homogeneous
Amelogen Plus A2	3.34 (0.10)	o, p	Radiopaque	Inhomogeneous with large number of irregular radiolucent inclusions ~200 and ~1,300 μm in diameter
Ceram X duo D2	3.53 (0.11)	p, q	200 % Al	Inhomogeneous with a number of irregular radiolucent inclusions ~650 μm in diameter
IPS Empress Direct Dentin A2	3.70 (0.11)	q, r	350 % Al	Homogeneous
Te-Econom Plus A2	3.76 (0.09)	q, r	300 % Al	Homogeneous
Tetric EvoCeram A2	3.82 (0.10)	r	400 % Al	Homogeneous
Clearfil AP-X A2	3.89 (0.12)	r	radiopaque	Homogeneous
Artemis A2 dentin	3.93 (0.11)	r	350 % Al	Homogeneous
Te-Econom A2	4.63 (0.15)	s	>250 % Al	Inhomogeneous with a number of irregular radiolucent inclusions ~1,300 μm in diameter

[a] Subsets demonstrating similar means ($p<0.05$)

Table 5 Radiopacity of 16 flowable resin composite materials with dentine and enamel radiopacity values as reference (mean (SD) equivalent thickness of aluminum for 1 mm sample thickness), with supplementary radiopacity values declared by manufacturers and description of the radiographic images of specimens

Material	Mean (SD) (mm eq Al)	Subset[a]	Radiopacity value declared by the manufacturer	Description of the radiographic images of specimens
Dentine	1.03 (0.03)	a	/	/
Synergy Flow A2/B2	1.50 (0.12)	b	Radiopaque	Homogeneous
Gradia Direct LoFlo A2	1.50 (0.12)	b	Radiopaque	Homogeneous
Beautifil Flow F10 A2	1.68 (0.12)	b	150 % Al	Homogeneous
Beautifil Flow F02 A2	1.69 (0.10)	b, c	150 % Al	Homogeneous
Enamel	1.91 (0.07)	c, d	/	/
Te-Econom Flow A2	1.92 (0.13)	d	Radiopaque	Homogeneous
Filtek Supreme XT Flowable A2	2.09 (0.10)	d, e	189 % Al	Homogeneous with very rare round radiopaque inclusions ~250 µm in diameter
Gradia Direct Flo A2	2.12 (0.11)	d, e, f	Radiopaque	Homogeneous
Venus Flow A2	2.17 (0.12)	e, f	Radiopaque	Homogeneous
Grandio Flow A2	2.27 (0.11)	e, f	Radiopaque	Homogeneous
G-ænial flo AO3	2.32 (0.12)	f	200 % Al	Inhomogeneous with large number of round radiopaque inclusions ~100 µm in size
G-ænial flo A3	2.33 (0.12)	f	Radiopaque	Inhomogeneous with large number of round radiopaque inclusions ~100 µm in size
X-flow A2	2.34 (0.12)	f	200 % Al	Homogeneous
PermaFlo A2	2.86 (0.10)	g	Radiopaque	Homogeneous
Tetric EvoFlow A2	2.99 (0.08)	g, h	360 % Al	Homogeneous with round radiolucent inclusions ~320 µm in size
Premise Flowable A2	3.14 (0.12)	h	333 % Al	Homogeneous with round radiolucent inclusions ~320 µm in size
Clearfil Majesty Flow A2	3.88 (0.12)	i	290 % Al	Homogeneous with round radiolucent inclusions ~200 µm in size

[a] Subsets demonstrating similar means ($p<0.05$)

sandwich restorations as an alternative to conventional composite materials, mainly because of their better resistance to microleakage [38]. On other hand, their radiopacity may be insufficient and/or they are inhomogeneous [39].

In our study, we tested 56 dental restorative materials which are commonly used on the gingival part of class II restoration. The results show that the radiopacity values of all 56 restorative materials were above the dentin reference radiopacity value ($p<0.05$). Therefore, none of the tested materials could be misinterpreted as dentinal caries on the radiographic image. However, 4 out of 33 conventional composites and 3 out of 16 flowable resin composites had significantly lower radiopacity than enamel ($p<0.05$). These composites, when put as a first increment on the gingival part of class II restoration, might be misinterpreted as secondary enamel caries on the radiographic image. Therefore, they should not be used as a first increment. Furthermore, four flowable composites and one conventional composite had the same radiopacity as enamel ($p<0.05$). On the radiographic image, these materials might not be distinguished from enamel. On the other hand, the radiopacity value of 13 conventional composites, 4 flowable composites, and 3 glass ionomer cements was equal or higher than 3 mm eq Al ($p<0.05$). These very radiopaque materials may mask caries lesion [29].

Although most of the A2 enamel and A2 dentinal shades of the same brand had similar radiopacity values, some dentinal shades had up to 1.31 mm eq Al higher mean radiopacity value compared to the same enamel shade. Similarly, there was also a difference among conventional and flowable resin composites. Most of the flowable resin composites had lower radiopacity values than conventional composites of the same brand. On the other hand, some flowable composites had up to 1.04 mm eq Al higher mean radiopacity value. These differences were probably a result of the different types and percentages of the filler in the composites.

For around half of the tested materials, the manufacturers did not provide the exact radiopacity values of the materials

Table 6 Radiopacity of seven restorative glass ionomer cement materials with dentine and enamel radiopacity values as reference (mean (SD) equivalent thickness of aluminum for 1 mm sample thickness), with supplementary radiopacity values declared by manufacturers and description of the radiographic images of specimens

Material	Mean (SD) (mm eq Al)	Subset[a]	Radiopacity value declared by the manufacturer	Description of the radiographic images of specimens
Dentine	1.03 (0.03)	a	/	/
Enamel	1.91 (0.07)	b	/	/
Fuji IX GP Extra A2	2.13 (0.12)	c	Radiopaque	Homogeneous with round radiolucent inclusions ~320 μm in size and radiolucent crack lines
GlasIonomer FX-II A2	2.49 (0.17)	d	Radiopaque	Homogeneous with round radiolucent inclusions ~320 μm in size
Ionofil Molar AC Quick A2	2.53 (0.11)	d	250 % Al	Homogeneous
Ketac Molar Quick Aplicap A2	2.63 (0.11)	d	260 % Al	Homogeneous
Ketac N100 A2	2.94 (0.11)	e	Radiopaque	Homogeneous
Fuji II LC capsule A2	3.10 (0.13)	e	Radiopaque	Homogeneous with a number round radiolucent inclusions ~250 μm in size
Photac Fil Quick Aplicap A2	3.15 (0.14)	e	300 % Al	Homogeneous with a number round radiolucent inclusions ~200 μm in size

[a] Subsets demonstrating similar means ($p<0.05$)

and merely declared their material to be radiopaque. When comparing the results of this study with the available radiopacity values declared by the manufacturers, we see that most of the values are in accordance with our results. Nevertheless, there are some noticeable differences between the results of this study and the manufacturer-given radiopacity values. Three restorative materials with the biggest difference between the mean radiopacity value measured in our study and the manufacturer-decelerated radiopacity value were Ceram X duo D2 (+1.53 mm eq Al), Clearfil Majesty Flow A2 (+0.98 mm eq Al), and Ceram X duo E2 (+0.80 mm eq Al).

The visual examination of the radiographic images showed that most specimens were free of radiolucent and radiopaque inclusions. Even though all the specimens with visible inhomogeneities were replaced with new specimens before the acquisition of radiographs and special attention was paid not to include any additional air bubbles in the material, several specimens had inclusions. The most common were radiolucent inclusions, which probably presented the air inclusions. The least frequent radiopaque inclusions were probably the aggregates of radiopaque filler. Some of the tested materials had a large number of small inclusions throughout the material, giving the material its inhomogeneous appearance on the radiographs. It is our opinion that the radiographic images could also be used by the manufacturers as a simple and inexpensive tool to test the homogeneity of their products.

In addition to the presented in vitro radiopacity values, it is also important to consider variable clinical and radiographic factors affecting radiopacity, i.e., variations in material thickness [40] and composition [41], X-ray tube operating voltage [27], and beam direction [42]. We also have to consider that the statistically significant difference in radiopacity might not be observed by a dentist [2].

Aluminum is widely used as a radiographic standard, since it is well established that the radiopacity of pure (99.5 %) aluminum is close to that of human dentin [3, 26]. In order to compare radiopacity measurements done by different researchers, it is imperative that all radiopacity measurements are taken with a stepwedge made of aluminum of high purity. The ISO standard for resin-based filling materials requires the use of aluminum of at least 99.5 % purity [25]. It has been shown that using a stepwedge of an aluminum alloy with 4 % copper will lead to radiopacity measurements 50 % lower than the ones taken with 99.5 % aluminum [14]. Therefore, it was suggested that alloys with an aluminum content of at least 98 % by mass to be used and that alloys with more than 0.05 % copper or 1.0 % iron should be excluded [14]. In our study, we used an aluminum alloy 1050, with a typical chemical composition of minimum 99.5 % of aluminum, maximum 0.05 % of copper, and maximum 0.4 % of iron.

Although the use of 99.5 % pure aluminum is currently specified when testing using the ISO standard 4049 [25], it is advisable also to use the secondary standards of enamel and dentin [14]. The dentin and enamel reference radiopacity values in our study were 1.03 (0.03) and 1.91 (0.07)mm eq Al, respectively. The values of enamel and dentin are in agreement with previous studies where the dentin radiopacity was close to 1 mm eq Al and enamel radiopacity was close to 2 mm eq Al [17, 28, 43–45].

ISO standards also require the use of stepwedge with thickness of 0.5 to 5 mm in steps of 0.5 mm [25]. To reduce machining costs and to speed the measurement process, an increase of maximum step thickness and a reduction of step number were recommended [2, 12, 18, 46, 47]. Because of the nearly perfect linearity of the aluminum absorbance, only three steps can produce the regression line that is highly similar to the one created from the full set of stepwedge data [12]. For that reason, we decided to use the stepwedge with steps of 1.00, 2.00, 4.00, and 8.00 mm. Any errors created by using the simplified regression are negligible in light of the fact that the exact elemental composition of the stepwedge, accuracy of the stepwedge, and specimen thickness will influence the measured radiopacity [14]. To ensure 1 % accuracy of the measurements, the material and tooth specimen thickness was measured with a digital caliper to be inside the 2.00±0.02 mm limits.

In our study, we used a digital radiographic system. The digital system reduces the operator's (and patient's) exposure to radiation, eliminates the need for film development chemicals, offers higher resolution and greater dynamic range than X-ray film, facilitates image analysis, and most importantly, provides consistent radiograph "development" [13, 48–53]. Traditional film development, unless performed carefully, can produce significant variations in the final radiograph [52]. However, to avoid the possible

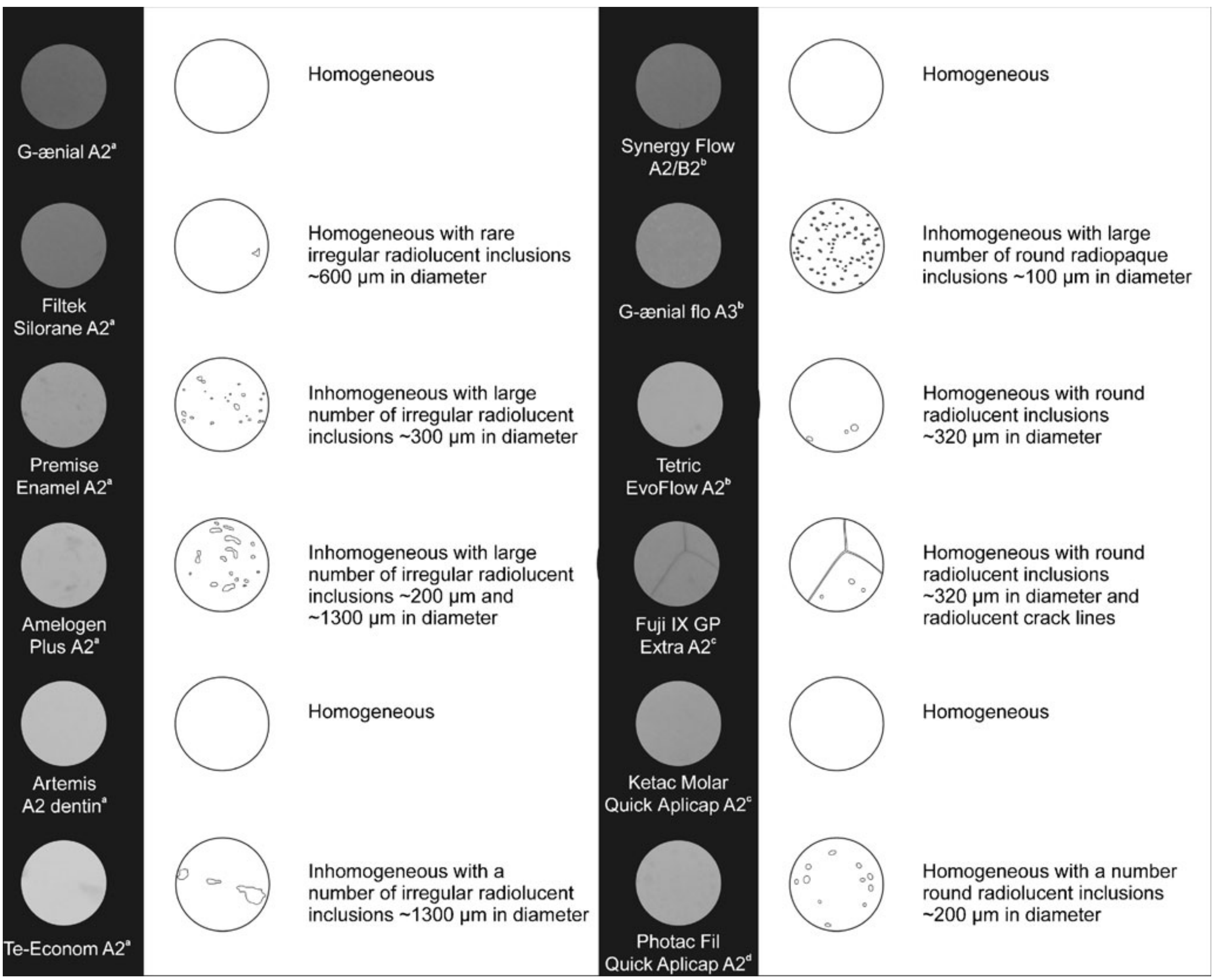

Fig. 1 Radiographs with sketches of the selected six conventional resin composites (*a*), three flowable resin composites (*b*), two conventional glass ionomer cements (*c*), and one resin-modified glass ionomer cement (*d*) specimens with different homogeneities and radiopacity values. On the *right side* is a description after the evaluation of inclusions in specimens: the relative number, shape, radiopacity/radiolucency, and size. For more data on the materials, see Tables 1, 2, 3, 4, 5, and 6

distortion of the results in the radiopacity measurements, it is necessary to acquire images without automatic gain control or other post-acquisition processing [13].

Conclusions

The radiopacity values of all 56 restorative materials were above the dentin reference radiopacity value; however, 4 out of 33 conventional composites and 3 out of 16 flowable resin composites had significantly lower radiopacity than enamel ($p<0.05$). These composites, when put as an initial increment on the gingival part of class II restoration, might be misinterpreted as enamel secondary caries on radiographic image. Additionally, radiopacity data provided by manufacturers could not be always relied on.

Conflict of interest The authors declare that they have no conflict of interest.

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