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RESEARCH ARTICLE

# Radiographic Evaluation of Current Restorative CAD/CAM Ceramics Indicated for Fabrication of Indirect Restoration

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## ABSTRACT

**Objectives:** To measure and compare the radiopacity values of available computer-aided design/computer-aided manufacturing (CAD/CAM) restorative materials used for the fabrication of long-term single-tooth indirect restorations.

**Materials and Methods:** 1 and 2 mm thick samples ($n = 10$ per material) were fabricated from different CAD/CAM materials, including glass-matrix (VITA mark II, Empress CAD, VITA Suprinity, Celtra DUO, and e.max CAD), polycrystalline (3Y zirconia, Katana HTML Plus), and resin-matrix ceramics (VITA Enamic, Lava Ultimate, Flexcera Smile Ultra Plus, Sprintray Ceramic Crown, VarseoSmile TriniQ, and Rodin Sculpture 2.0). The samples were placed on a digital X-ray sensor along with an aluminum step wedge and a tooth section with similar thickness. The gray scale value was measured in Image J software and converted to mmAl using Curve Expert Pro 2.7 software. Data were analyzed with a two-way ANOVA and post hoc Tukey tests, with the significance level set at 95% ($\alpha = 0.05$).

**Results:** Type of restorative material and thickness had a significant effect on the radiopacity values ($p < 0.05$). Radiopacity of all tested materials was similar to (Sprintray Ceramics Crown, $p > 0.05$) or significantly higher ($p < 0.05$) than the radiopacity of the dentin, except for VITA Mark II, VITA Enamic, Flexcera Smile Ultra Plus, and VarseoSmile TriniQ, which had a significantly lower radiopacity than dentin ($p < 0.05$).

**Conclusion:** Radiopacity of evaluated CAD/CAM materials was significantly different. The highest radiopacity was observed in zirconia, and the lowest radiopacity was found in Flexcera Smile Ultra Plus.

**Clinical Significance:** Radiopacity of most of the tested CAD/CAM materials was equal to or higher than that of dentin with a similar thickness. However, VITA mark II, VITA Enamic, Flexcera Smile Ultra Plus, VarseoSmile TriniQ had lower radiopacity than dentin and their radiographic evaluation would be dependent on the radiopacity of the cement for detection of recurrent caries. Understanding the radiopacity of each CAD/CAM material helps clinicians select the appropriate material and helps them detect the type of restorative material.

## 1 | Introduction

Technological advancements in the field of dental manufacturing of indirect restorations have progressed and revolutionized the fabrication of metal-free restorations. Ceramic restorations have become popular among clinicians over the last two decades mainly due to favorable mechanical (fracture and wear resistance), optical (mimicking translucency of natural tooth), biological (inertness and biocompatibility), thermal characteristics (appropriate thermal insulation), and chemical stability (resistance to pH and temperature changes, and exposure to stains) [1]. Moreover, modern ceramic restorations offer a lower production cost and a more efficient manufacturing workflow, which has resulted in the selection of these materials over conventional metal-ceramic restorations by clinicians in recent years, according to a nationwide survey [2].

A wide range of ceramic materials is available for manufacturing indirect restorations, and one of the most efficient approaches to classify these materials is based on the composition/microstructure of the material. In this regard, modern ceramics can be classified into three categories: glass-matrix, polycrystalline, and resin-matrix ceramics [1, 3]. This classification enables clinicians to recognize the properties and clinical indications of each specific material. In addition, it would help clinicians to navigate the optimal surface treatment when delivering the indirect restoration with a resin cements [4, 5]. Ceramics can also be classified based on the manufacturing techniques, including slip-casting, layering, heat pressing, subtractive (also called milling) computer-aided design/computer-aided manufacturing (CAD/CAM), and additive (also called 3D printing) CAD/CAM techniques [6–10].

Restorative materials and the cement used to lute the restoration in place are required to have sufficient radiopacity to facilitate the detection of secondary caries, marginal integrity, missing proximal contact point, and excess cement on a dental radiograph [11–13]. To detect secondary caries, the radiopacity of the material is required to be equal to or higher than the radiopacity of dentin [8]. Moreover, detection and localization of restorative materials is necessary in case of swallowing or aspirating the restoration [14, 15]. Radiopacity of the restorative materials is also helpful in forensic medicine [16]. Radiopacity of a restorative material depends on its composition including the matrix (glass, polycrystalline, or resin) and the composition and percentage of the filler particles (leucite, lithium disilicate, lithium silicate, zirconia, alumina, silica) [11, 13, 17]. Both the glass matrix, which is predominantly composed of silicon dioxide, and the resin matrix in 3D printable restorative materials, which is methacrylate-based, lack heavy metal elements, contributing to the lower radiopacity of these materials. On the other hand, adding filler particles containing heavy metals increases the radiopacity of the restorative material [8–10, 14]. 3D printable restorative materials have shown to contain various types of methacrylate resins as the matrix and various sizes and shapes of silica fillers which might result in lower radiopacity values than other CAD/CAM restorative materials [8].

Radiopacity of dental materials is evaluated and measured with an optical density value or an equivalence to an aluminum thickness (mmAl) measured with an aluminum wedge with different thicknesses to produce a reference calibrated curve [13, 18–20]. Since the radiopacity of dentin is equal to aluminum, the International Organization for Standardization (ISO) specifies that the radiopacity of restorative dental materials should be equal to or greater than the radiopacity of aluminum (with $\geq 98\%$ purity) with the similar thickness [21–24].

Although the radiopacity of subtractive CAD/CAM materials has been investigated in the literature [11–13, 25–30], there is not sufficient data on the additively manufactured CAD/CAM materials used for indirect restoration. Hence, the aim of the present study was to evaluate the radiopacity of 12 different CAD/CAM restorative materials that were manufactured with either subtractive or additive manufacturing. The first null hypothesis of the present study was that the radiopacity of the tested materials would be no different from the radiopacity of dentin. Additionally, the filler weight percentage of the additively manufactured CAD/CAM materials was determined to assess the effects of filler content on radiopacity. The second null hypothesis was that the filler content would not affect radiopacity.

## 2 | Materials and Methods

### 2.1 | Sample Preparation

An .stl file was created in a CAD software (Blender, Blender Foundation, Amsterdam, the Netherlands) in the form of a 5 mm × 5 mm square. The .stl file was used to fabricate the materials ($n = 20$ per material) listed in Table 1. CAD/CAM blocks were milled in a 5-axis milling unit (MC X5, Dentsply Sirona) into a long rod with a cross section of 5 mm × 5 mm and then sectioned into 1 mm ($n = 10$ per material) and 2 mm ($n = 10$ per material) squares using a cutting machine (Accutom, Struers, Copenhagen, Denmark) under running water. These samples were then crystallized or sintered based on the manufacturer's instructions.

Extracted human premolars were collected following Institutional Review Board approval. The premolars were wet-ground through their occlusal surface until all occlusal enamel was removed. The specimens were then sectioned into 1 or 2 mm sections using a cutting machine (Accutom, Struers). One premolar was used for each section.

One of the 3D-printed materials (Flexcera Smile Ultra+, Desktop Health, Newport Beach, CA, USA) was fabricated using a DLP printer (Einstein, Desktop Health). The samples were positioned in the slicing software (Envision One RP, Desktop Health) with 5 mm × 1 mm or 5 mm × 2 mm faces parallel to the build plate, and the layer thickness was set at 100 μm. After printing, the excess resin was cleaned in a washing unit (PWA 2000, Desktop Health) using 99% IPA and then post-cured in a curing unit (Otoflash G171, NK Optik, Baierbrunn, Germany) according to the manufacturer's recommendation of 3000 flashes per side (total of 6000 flashes).

Another 3D-printed sample (Sprintray Ceramic Crown, Sprintray, Los Angeles, CA, USA) was printed using a DLP printer (Pro55S, Sprintray). In the slicing software (RayWare Cloud, Sprintray), the samples were positioned with 5 mm × 1 mm or 5 mm × 2 mm faces parallel to the build plate and layer thickness set at 100 μm (Figure 1). After printing the samples, the excess resin was cleaned with 99% isopropyl alcohol (IPA) and postcured in a curing unit (ProCure 2, Sprintray) using preprogrammed settings.

Other 3D-printed material (VarseoSmile TriniQ, BEGO, Bremen, Germany) was fabricated using another DLP printer (Asiga Ultra, Asiga, Sydney, Australia) The samples were positioned in the slicing software with 5 mm × 1 mm or

**TABLE 1** | Materials evaluated in this study.

| CAD/CAM material | Type of material | Composition | Manufacturing method | Manufacturer |
|---|---|---|---|---|
| VITA Mark II | Feldspar-reinforced aluminosilicate glass | < 20% wt feldspathic particles[a] > 80% wt glass matrix | Subtractive (milling) | VITA Zahnfabrik |
| Empress CAD | Leucite-reinforced glass ceramic | 64.9% $SiO_2$, 16.25% $Al_2O_3$, 11.85% $K_2O$, 5.37% $Na_2O$, 1.56% CaO[a] | Subtractive (milling) | Ivoclar Vivadent |
| VITA Suprinity | Zirconia reinforced lithium-silicate glass ceramic | 56%–64% $SiO_2$, 15%–21% $Li_2O$, 1%–4% $K_2O$, 3%–8% $P_2O_5$, 1%–4% $Al_2O_3$, 8%–12% $ZrO_2$, 0%–4% $CeO_2$, 0.1% $La_2O_3$[a] | Subtractive (milling) | VITA Zahnfabrik |
| Celtra DUO | Fully sintered zirconia reinforced lithium-silicate glass ceramic | 58% $SiO_2$, 5% $P_2O_5$, 1.9% $Al_2O_3$, 18.5% $Li_2O$, 10.1% $ZrO_2$, 1% $Tb_4O_7$, 2% $CeO_2$[a] | Subtractive (milling) | Dentsply Sirona |
| E.max CAD | Lithium-disilicate glass ceramic | 57%–80% $SiO_2$, 11%–19% $LiO_2$, 0%–13% $K_2O$, 0%–11% $P_2O_5$, 0%–8% ZrO2, 0%–8% ZnO, 0%–5% $Al_2O_3$, 0%–5% MgO[a] | Subtractive (milling) | Ivoclar Vivadent |
| Katana HTML Plus | Polycrystalline ceramic | 87%–89% $ZrO_2$, < 2% $HfO_2$, 5.2% $Y_2O_3$, < 2% other oxides including $Al_2O_3$[a] | Subtractive (milling) | Kuraray Noritake |
| VITA Enamic | Resin-matrix ceramics, polymer-infiltrated reinforced-glass network | 86% wt feldspathic-based ceramic network, 14% wt acrylate polymer network[a] | Subtractive (milling) | VITA Zahnfabrik |
| Lava Ultimate | Resin-matrix ceramics, resin nanoceramic | 80% wt nanoceramics including $SiO_2$ and $ZrO_2$, 20% wt highly cross linked polymer matrix[a] | Subtractive (milling) | 3 M ESPE |
| Flexcera Smile Ultra Plus | Resin-matrix ceramics | $SiO_2$ filler particles, resin | Additive (3D printing) | Desktop health |
| Sprintray Ceramic Crown | Resin-matrix ceramics | $SiO_2$ with Yb filler particles, resin | Additive (3D printing) | Sprintray |
| Varseosmile TriniQ | Resin-matrix ceramics | $BaO{\cdot}Al_2O_3{\cdot}2SiO_2$ filler, resin | Additive (3D printing) | Bego |
| Sculpture 2.0 | Resin-matrix ceramics | $BaO{\cdot}Al_2O_3{\cdot}2SiO_2$ and $ZrO_2$ filler, resin | Additive (3D printing) | Rodin |

[a]Based on manufacturer's information.

5 mm × 2 mm faces parallel to the build plate and layer thickness set at 100 μm. After printing, the excess resin was cleaned by gently rubbing with 99% IPA and then post-cured in a curing unit (Otoflash G171, NK Optik) according to the manufacturer's recommendation of 2000 flashes per side (total of 4000 flashes).

The last 3D-printed material (Rodin Sculpture 2.0, Pac-Dent International Inc., Brea, CA) was fabricated using an LCD printer (Phrozen Sonic Mini 8K, Hsinchu City, Taiwan). The samples were positioned in the slicing software (Envision One RP, Desktop Health) with the 5 mm × 1 mm or 5 mm × 2 mm face parallel to the build plate and the layer thickness set at 100 μm. After printing, the excess resin was cleaned by gently rubbing with 99% IPA and then post-cured in a curing unit (Otoflash G171, NK Optik) according to the manufacturer's recommendation of 2500 flashes per side (total of 5000 flashes).

Specimens were polished with a series of SiC abrasive papers (60-, 180-, 320-, 600-grit) using a rotational polishing unit. All polishing was performed on both sides, parallel to the straight edge of the specimen, and repeated following a 90° rotation. Specimens were evaluated after polishing, and in case of stray scratch presence, the polishing was repeated. The final thickness of the samples was 1.0 ± 0.03 or 2.0 ± 0.03 mm, as verified by an electronic caliper.

## 2.2 | Radiopacity Measurement

The specimens were placed on a digital X-ray sensor (Schick 33 size 2 sensor, Dentsply Sirona) next to a tooth section with similar thickness. A 16-mm aluminum step wedge (each step 1 mm in thickness) with 99.99% purity (High Purity Aluminum, Boca Raton, FL, USA) was placed on the X-ray sensor with the specimens (Figure 2). The specimens were exposed by a dental X-ray unit (65 KVp, 0.3 s exposure at 10 mA) with the focal spot distance (target-film distance) of 35 cm according to ISO 13116.

Ten digital images were obtained for 1 mm thick samples and 10 digital images for 2 mm thick samples. Digital images were then exported to ImageJ software (National Institute of Health) to analyze and measure the greyscale. The mean greyscale value was measured from five different locations of each sample and was averaged to obtain the mean greyscale value of each sample in each digital image. In addition, the average greyscale value of each step of the aluminum wedge was calculated to obtain the reference greyscale values. A non-linear trendline (Figure 3) was

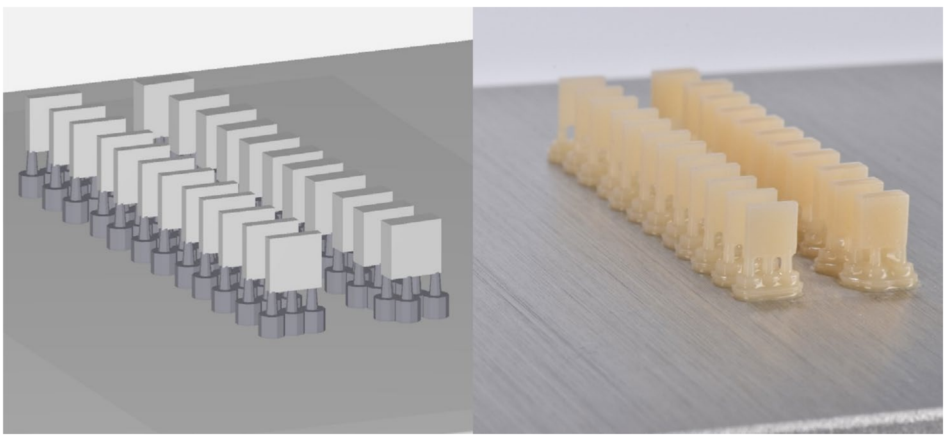

**FIGURE 1** | Positioning the designed .stl file in slicing software (left side) and printed samples (right side).

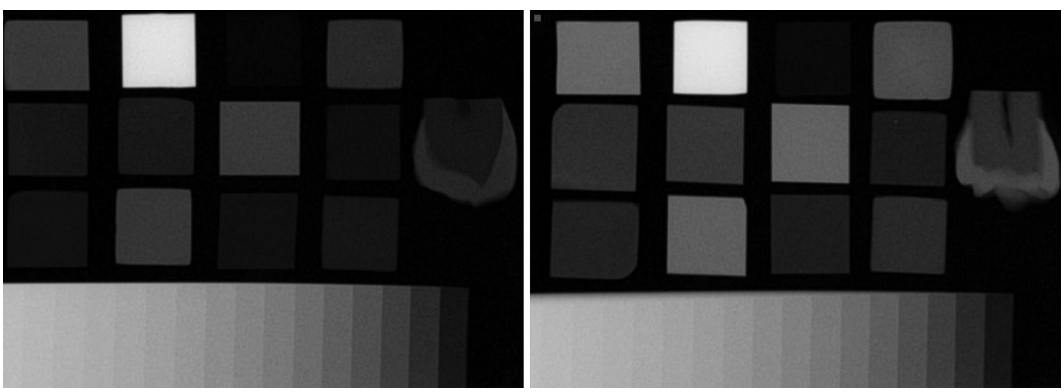

**FIGURE 2** | Digital images obtained from 1 mm thick (left side) and 2 mm thick (right side) samples along with a tooth section with similar thickness and the aluminum wedge.

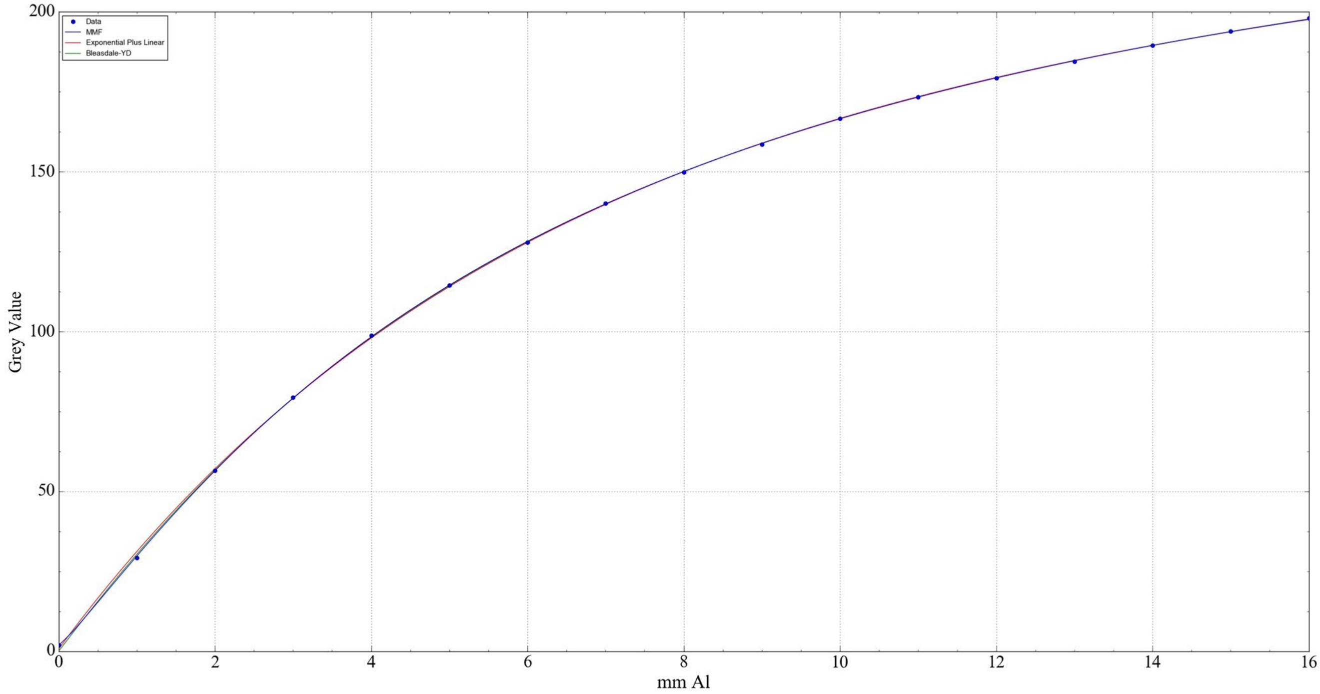


**FIGURE 3** | Trendline plotted in Curve Expert Pro software for the aluminum wedge in each digital image to measure the corresponding mmAl of the specimens.

plotted for each digital image in Curve Expert Pro 2.7.3 (Curve Expert.net, US) and used to determine the corresponding mmAl of each sample.

### 2.3 | Filler Content Measurement

An aliquot of 5 mL of the 3D-printed resin composites (Flexcera Smile Ultra+, Sprintray Ceramic Crown, VarseoSmile TriniQ, and Rodin Sculpture 2.0, $n = 5$ per material) was transferred into a high-alumina 20 mL crucible (Sigma Aldrich, St. Louis, MO, USA). The initial mass ($W_0$) of the samples was measured using an analytical balance with a precision of 0.0001 g (AE163, Mettler Toledo, Greifensee, Switzerland). To eliminate the organic matrix, the samples were heated in an electric furnace at 800°C for 30 min. After heating, the samples were allowed to cool for 15 min, and the remaining inorganic filler was reweighed ($W_1$). The weight percentage of the filler (wt %) was calculated using the formula: Filler wt % $= (W_1/W_0) \times 100\%$.

The ash from the burned materials was lightly distributed onto a SEM stub coated with conductive tape. The specimens were then gold-coated using a vacuum sputter coater and analyzed in secondary electron imaging mode on a SEM (Quanta FEG 650; FEI, Hillsboro, OR, USA). Two specimens from each group were examined to confirm consistency. Energy dispersive spectroscopy (EDS) was used to analyze the surface elemental composition of the isolated filler particles, with an electron energy range of 10–25 keV. For each material, the elemental composition across the entire viewing area was selected to ensure elemental identification from each type of filler.

### 2.4 | Statistical Analysis

The number of readings for all groups was determined using statistical calculations following a pilot study. The statistical analyses of the pilot study were carried out using GPower 3.1.9.7 software for two-way analysis of variance (ANOVA) within factors, an $\alpha$ err prob. $= 0.05$, power (1-$\beta$ err prob) $= 0.80$, effect size of 0.4, and a total of 28 groups. A two-way ANOVA test was used and followed by a post hoc tukey test. A linear regression was run to understand the effect of filler wt % on radiopacity. Statistical analyses were performed in SPSS version 29.0 software (IBM SPSS Statistics, Armonk, NY, USA) and all of the statistical tests were two-sided, and the significance level was set at 0.05.

## 3 | Results

The results of the radiopacity values based on the corresponding mmAl are presented in Table 2 and Figure 4. The highest radiopacity was observed in zirconia, and the lowest radiopacity was found in Flexcera Smile Ultra Plus. A comparison of the radiopacity of different CAD/CAM materials revealed that both the type of material and thickness had a significant effect on the radiopacity values ($p < 0.001$). According to the post hoc Tukey test, no significant difference was found between enamel and Rodin Sculpture, dentin and Empress CAD, or Sprintray Ceramic Crown ($p > 0.05$). The radiopacity of VITA Suprinity, Celtra DUO, Zirconia, Lava Ultimate, and Rodin Sculpture was significantly higher than that of enamel, and the radiopacity of VITA Mark II, VITA Enamic, Flexcera Smile Ultra Plus, and VarseoSmile TriniQ was significantly lower than that of dentin ($p < 0.001$).

**TABLE 2** | Descriptive statistics of radiopacity.

| Specimen | 1 mm Thick | | 2 mm Thick | |
|---|---|---|---|---|
| | Grayscale value (mean ± SD) | Radiopacity* (mmAl) (mean ± SD) | Grayscale value (mean ± SD) | Radiopacity* (mmAl) (mean ± SD) |
| Enamel | 52.25 ± 0.91 | 1.83 ± 0.03[a] | 88.47 ± 0.56 | 3.51 ± 0.03[a] |
| Dentin | 31.96 ± 0.66 | 1.03 ± 0.02[b] | 58.09 ± 0.937 | 2.07 ± 0.04[b] |
| VITA Mark II | 23.12 ± 0.43 | 0.72 ± 0.01[c] | 44.82 ± 0.47 | 1.52 ± 0.02[c] |
| Empress CAD | 32.35 ± 0.89 | 1.04 ± 0.03[b] | 60.66 ± 1.31 | 2.18 ± 0.06[b] |
| VITA Suprinity | 74.00 ± 0.47 | 2.78 ± 0.02[f] | 122.90 ± 0.60 | 5.63 ± 0.04[f] |
| Celtra DUO | 70.82 ± 1.27 | 2.63 ± 0.06[g] | 114.70 ± 0.76 | 5.07 ± 0.05[g] |
| E.max CAD | 33.88 ± 0.45 | 1.10 ± 0.02[h] | 69.07 ± 1.15 | 2.55 ± 0.05[h] |
| Katana HTML Plus | 229.44 ± 0.76 | 16.00 ± 0.00[i] | 230.57 ± 0.68 | 16.00 ± 0.00[i] |
| VITA Enamic | 20.50 ± 0.32 | 0.62 ± 0.01[j] | 37.78 ± 0.79 | 1.25 ± 0.03[j] |
| Lava Ultimate | 75.31 ± 0.41 | 2.85 ± 0.02[k] | 117.01 ± 1.60 | 5.24 ± 0.10[k] |
| Flexcera Smile Ultra Plus | 5.69 ± 0.18 | 0.13 ± 0.01[l] | 9.19 ± 0.48 | 0.24 ± 0.02[l] |
| Sprintray Ceramic Crown | 31.34 ± 0.91 | 1.01 ± 0.03[b] | 56.98 ± 0.52 | 2.01 ± 0.02[b] |
| Varseosmile TriniQ | 17.11 ± 0.12 | 0.51 ± 0.01[n] | 34.68 ± 0.36 | 1.13 ± 0.02[n] |
| Rodin Sculpture 2.0 | 53.04 ± 1.54 | 1.86 ± 0.06[a] | 94.88 ± 0.56 | 3.86 ± 0.03[a] |

*Please note similar alphabets under each column indicate no significant difference based on Tukey post hoc test.

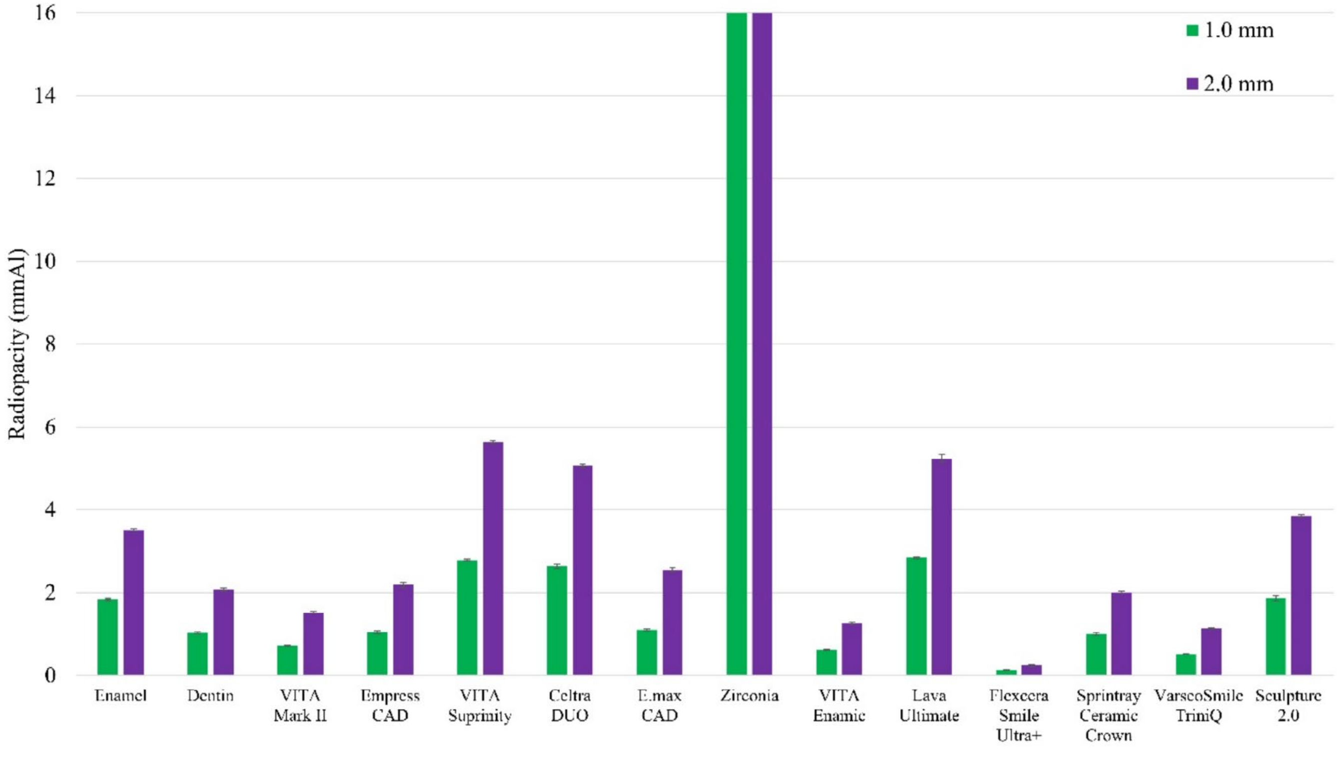


**FIGURE 4** | Radiopacity (mmAl) of enamel and dentin and tested materials.

The filler weight percentage of the 3D-printed resin composites was 14.8% ± 0.3% for Flexcera Smile Ultra+, 50.2% ± 0.7% for Sprintray Ceramic Crown, 20.4% ± 0.3% for VarseoSmile TriniQ, and 58.2% ± 0.9% for Rodin Sculpture 2.0. Statistical significance was not found for the regression model for a positive linear relationship between filler content and radiopacity at 1 mm

($p = 0.071$, $R_2 = 0.863$, Figure 5) or 2 mm ($p = 0.085$, $R_2 = 0.837$, Figure 5). Representative SEM images of the fillers from the 3D-printed resin composites are presented in Figure 6. The elemental composition of the fillers from Flexcera Smile Ultra+ was O and Si; from Sprintray Ceramic Crown, was O, Si, and Yb; from VarseoSmile TriniQ, was O, Al, Si, and Ba; and from Rodin Sculpture 2.0, was O, Al, Si, Zr, and Ba.

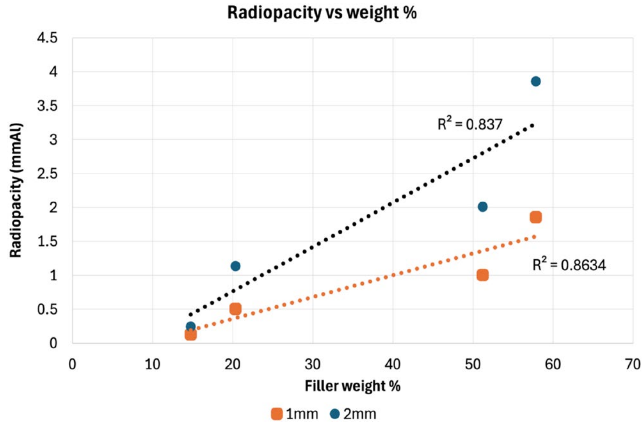


**FIGURE 5** | Radiopacity vs. filler wt% of the 3D-printed materials used in this study.

## 4 | Discussion

The objective of the present study was to evaluate and measure the radiopacity of different CAD/CAM materials available for fabrication of indirect restorations. The first null hypothesis was that the radiopacity of the tested materials would be no different than the radiopacity of dentin. According to the present findings, this null hypothesis was partially accepted as the radiopacity of some of the tested materials was equal to dentin with similar thickness, except VITA Mark II, VITA Enamic, Flexcera Smile Ultra Plus, and VarseoSmile TriniQ, which had lower radiopacity than dentin.

Based on the present findings, the composition of the tested materials had a significant impact on the radiopacity values. The highest radiopacity was found in zirconia samples, which was higher than the thickest step of the aluminum wedge. This

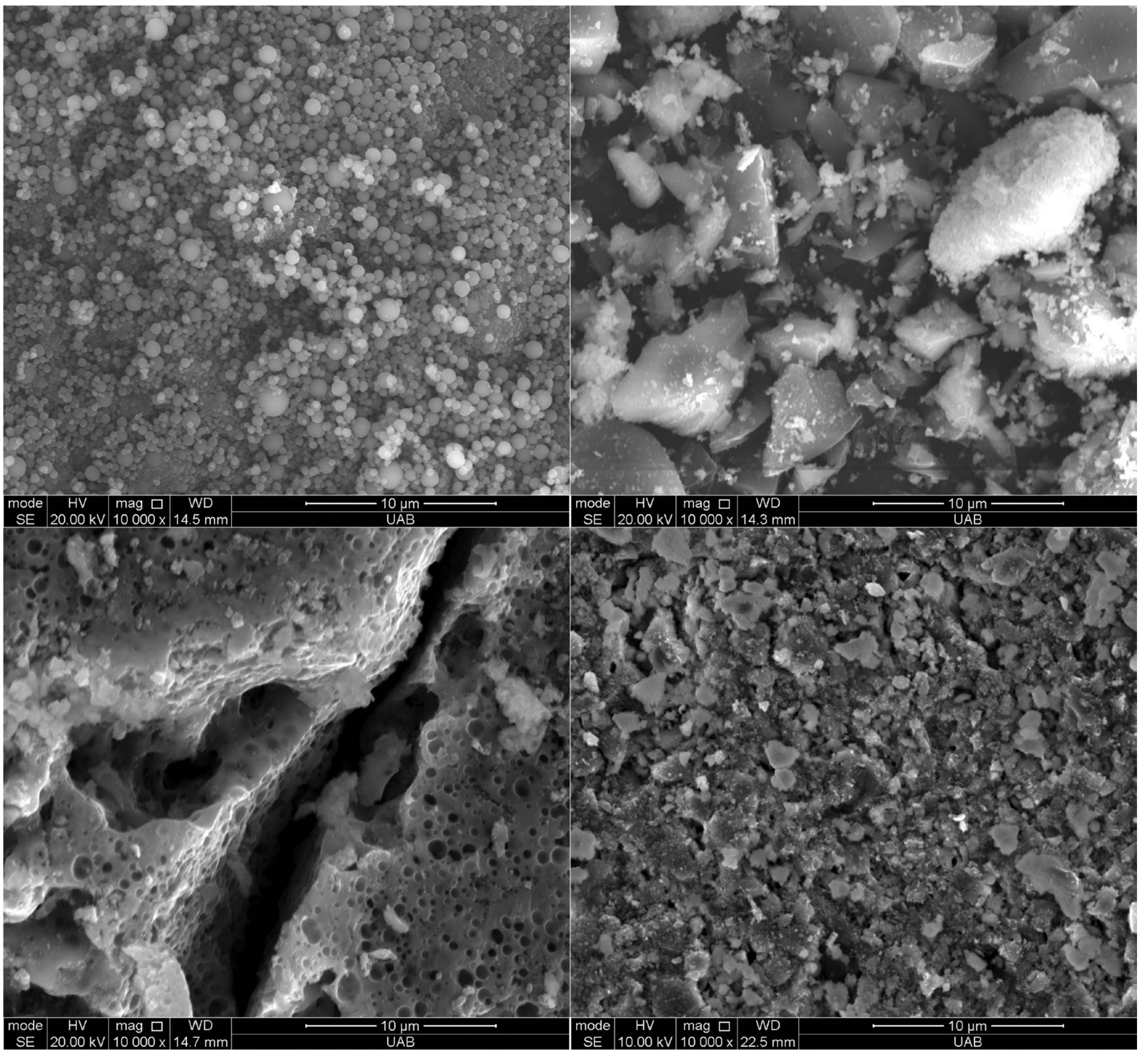


**FIGURE 6** | Filler content of 3D-printed resin composites, upper left to bottom right: Flexcera Smile Ultra+, Sprintray Ceramic Crown, Varseo Smile TriniQ, and Rodin Sculpture 2.0.

finding was similar to previous findings where the mean gray value of a zirconia sample was higher than the thickest aluminum step [11]. The presence of zirconium dioxide in the composition of VITA Suprinity, Celtra Duo, and Lava Ultimate could explain the higher radiopacity values of these materials in comparison to other tested materials and was similar to the previous findings [11–13, 26]. Although higher radiopacity would be helpful to detect secondary caries and marginal integrity, excessive radiopacity might reduce the ability to detect these findings in a radiograph due to the Mach effect, which is a visual illusion of a dark border created due to significant contrast between the radiopacity of two materials [26, 28, 29].

In the present study, the lowest radiopacity was found in two subtractive (VITA Mark II and VITA Enamic) and two additively manufactured (Flexcera Smile Ultra Plus and VarseoSmile TriniQ) CAD/CAM materials, which had radiopacity lower than that of dentin. Similar to the present findings, Atala et al. [13], Koizumi et al. [14] and Babaier et al. [25] found the radiopacity of VITA Mark II and VITA Enamic to be less than that of dentin. In contrast, Elhelbawy et al. [26] found the radiopacity of VITA Enamic to be higher than that of dentin. This contrast could be related to the difference in the radiography system used. The reason for the low radiopacity value of these CAD/CAM blocks could be the dense glass matrix, which lacks heavy metal elements. Similarly, the 3D printable materials contain high amounts of methacrylate-based matrix and a lack of heavy metal elements in the filler particles [8]. Low radiopacity may reduce the chance of detecting faulty margins and proximal contours, and the detection of recurrent caries would be dependent on the radiopacity of the luting cement [30]. Therefore, it is suggested to increase the radiopacity of these restorative materials by adding heavy metals, including barium, zirconium, or strontium [9, 10, 14, 26].

The second null hypothesis was that filler weight percentage would not affect the radiopacity of 3D printed materials. This hypothesis could not be rejected as the linear relationship between filler weight and radiopacity was not significant; however, this result could be related to the small number of data points used for this analysis. There was a trend towards greater radiopacity for higher filled materials. A previous study of 16 resin composites reported a significant positive linear correlation between filler weight percentage; however, the fit of that regression line was much lower ($r=0.36$) than the current study [17]. Aside from the filler weight percentage, the different 3D printed materials had different radiopacifiers in their composition: Sprintray Ceramic Crown contained ytterbium (Yb, atomic number 70), VarseoSmile TriniQ and Rodin Sculpture 2.0 contained glass with barium (Ba, atomic number 56), and Rodin Sculpture 2.0 contains ceramic with zirconium (Zr, atomic number 40).

It has been reported that the radiopacity of the restorative material used as an indirect restoration should compare to the radiopacity of tooth structure and aluminum with similar thickness [13, 18]. The radiopacity of tooth structure, including enamel and dentin, is reported in equivalent millimeters of aluminum, and the radiopacity of a pure aluminum is close to dentin according to ISO standard 4049 [21]. In the present study, the mean radiopacity of dentin with 1 mm thickness was equal to 1.029 mmAl, and 2 mm thickness to 2.069 mmAl. Enamel had higher radiopacity at 1 mm (1.826 mmAl) and 2 mm (3.513 mmAl). These findings are comparable to the radiopacity of dentin and enamel reported in previous studies [11–14, 25–27].

Different variables may influence the radiopacity value of the same material, including the imaging technique, exposure factors (kVP, mA, exposure time), angle of the X-ray beam with the object and film, and the distance between the focal spot and the film [13, 22–24]. In the present study, digital radiography was used to capture the digital images. Digital radiography allows for the use of a lower dose of radiation, rapid development of the image, and eliminates the potential processing errors of conventional films [30]. Digital radiographs can be obtained using two different systems, including phosphor plate and solid-state detector (Charged Coupled Device or Complementary Metal Oxide Semiconductor-Active Pixel Sensor). In the present study, a charged coupled device sensor system was used to capture the radiographs, and then the digital images were analyzed in image analysis software similar to previous studies [11–13, 25, 27].

The present study had multiple limitations. First, it was conducted in vitro, whereas in the oral environment, soft tissue can interact with the radiographic exposure of restorative materials. This interaction with the radiopacity of the materials was eliminated in the present study. Moreover, only a limited number of commercially available materials were included; future studies incorporating a higher number of available restorative materials would be recommended. Additionally, the role of the luting cement in the radiopacity of the restoration was not considered in the present study. Future studies to evaluate the interaction of different cements with restorative materials to provide a more comprehensive analysis are encouraged.

## 5 | Conclusion

Based on the present study, the following conclusions may be drawn:

1. Radiopacity of milled restorative ceramic materials varied from low radiopacity (VITA mark II and VITA Enamic), close to dentin (Empress CAD and E.max CAD), to the highest radiopacity observed in zirconia and zirconia-containing ceramics (VITA Suprinity, Celtra Duo, Lava Ultimate).
2. Radiopacity of 3D printable restorative ceramic material varied from very low radiopacity (Flexcera Smile Ultra Plus and VarseoSmile TriniQ), similar to dentin (Sprintray Ceramic Crown), to high radiopacity (Rodin Sculpture 2.0, close to enamel).
3. Although not statistically significant, there was a trend for higher-filled 3D-printed materials to demonstrate greater radiopacity.

**Conflicts of Interest**

The authors declare no conflicts of interest.

**Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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