

# Micro-CT Detection and Characterization of Porosity in Luting Cements

Meral Arslan Malkoç, DDS, MsD, PhD,<sup>1</sup> Müjde Sevimay, DDS, MsD, PhD,<sup>2</sup> İlkan Tatar, MsD,<sup>3</sup> & Hakan Hamdi Çelik, MsD<sup>3</sup>

<sup>1</sup>Department of Prosthodontic Dentistry, Faculty of Dentistry, İnönü University, Malatya, Turkey

<sup>2</sup>Department of Prosthodontic Dentistry, Faculty of Dentistry, Selcuk University, Konya, Turkey

<sup>3</sup>Department of Anatomy, Medical School, Hacettepe University, Ankara, Turkey

## Keywords

Micro-CT; porosity; dental cements; ceramic crown.

## Correspondence

Meral Arslan Malkoç, İnönü University, Faculty of Dentistry, Department of Prosthodontics, Malatya 44280, Turkey. E-mail: mrlmalkoc@hotmail.com

*Abstract presented at FDI 2013 Istanbul Annual World Dental Conference, August 28, 2013.*

*This study was based on the work performed by Meral ARSLAN MALKOÇ for the fulfillment of the degree of Doctor of Philosophy, Selcuk University, Turkey. This study was supported by Selcuk University BAP (09102035).*

*The authors deny any conflicts of interest.*

Accepted June 8, 2014

doi: 10.1111/jopr.12251

## Abstract

**Purpose:** To evaluate porosity volume and localization in luting cements under fixed dental prostheses after cementation using micro-computed tomography (CT).

**Materials and Methods:** Seventy-seven sound molars were circumferentially prepared to receive all-ceramic crowns, and IPS e.max ceramic copings were fabricated according to the manufacturer's instructions. For this study, different dental luting cements were used: eight resin-based cements (Variolink II, RelyX ARC, Clearfil Esthetic, BisCem, RelyX U100, Panavia EX, Super Bond C&B, and Multilink Automix), one resin-modified glass ionomer (Ketac Cem Plus), one glass ionomer (Ketac Cem), and one polycarboxylate (Durelon). Specimens were scanned with a micro-CT (SkyScan) for detection and comparison of the cements' porosities. Statistical analyses were performed using Kruskal-Wallis one-way ANOVA and Bonferroni's adjusted Mann-Whitney U tests.

**Results:** Multilink Automix (Volume =  $0.11 \pm 0.08 \text{ mm}^3$ ; Surface Area =  $1.63 \pm 1.31 \text{ mm}^2$ ), Ketac Cem Plus (Volume =  $0.22 \pm 0.21 \text{ mm}^3$ ; Surface Area =  $4.32 \pm 3.71 \text{ mm}^2$ ), and Variolink II (Volume =  $0.34 \pm 0.38 \text{ mm}^3$ ; Surface Area =  $6.47 \pm 5.10 \text{ mm}^2$ ) contained less porosity ( $p < 0.001$ ) than all other cements. All other cements were not significantly different from one another ( $p > 0.05$ ); however, the volume and surface area of the porosity found in the other tested luting cements were significantly greater than those of the Multilink Automix, Ketac Cem Plus, and Variolink II ( $p < 0.001$ ), all of which demonstrated no significant differences ( $p > 0.05$ ).

**Conclusion:** The liquid and powder forms prepared by manually mixing the cements were found to cause greater porosity.

The role of dental cement has primarily relied on mechanical requirements and retention by simply filling in the gaps between the restoration and tooth structure. Integral adaptation of crowns and successful cementation have always been clinical concerns for dentists, as they are the most important elements in the long-term clinical success of restorations. A homogenous cement layer between the crown and tooth is required to avoid porosities forming in dental cement.<sup>1,2</sup>

Although dental luting cements are only used in small amounts, they may be the most critical materials in prosthodontics, due to their applications as luting agents to bond preformed restorations.<sup>1</sup> Generally, current dental luting cements consisting of inorganic fillers and a polydimethacrylate matrix are polymerized by rapid free-radical reactions, and these materials are becoming increasingly popular and preferred for direct restorations, such as ceramic crowns.<sup>3</sup> Volume loss during the

polymerization and cementation process generates stress that has been recognized as an important factor affecting the integrity between the restoration and tooth structure, leading to failure from the surrounding tooth structure and the formation of porosities or gaps.<sup>4-6</sup> Porosities incorporated into the materials may lead to inhibition zones with unpolymerized materials, which may result in higher water solubility and microleakage.<sup>2</sup> Porosity has an exponential effect on reducing strength, and as little as 10% porosity can reduce the overall strength by 50%.<sup>7</sup> Porosity may also greatly affect the longevity and success of a restoration.<sup>8</sup>

Over the last 10 years, micro-CT has gained popularity in examining tooth structures and dental restorations. Micro-CT is a nondestructive 3D method very suitable for investigating the details of the tooth structure and restoration relationship.<sup>9-12</sup> Well-designed clinical and in vitro research data have been

gathered regarding the mechanical or biological effects of dental luting cements and restorations.<sup>13-16</sup> However, no data have been published related to the internal structure of dental cement after the cementation procedure. The aim of this study was to evaluate porosity volume and localization in cements under complete ceramic crowns using micro-CT. The tested null hypothesis was that there are no differences in the volumes or surface areas with regard to porosity among the different luting cements, after polymerization under a complete ceramic crown.

## Materials and methods

This study was approved by the Ethics Committee of the Faculty of Dentistry of Selcuk University (Konya, Turkey; Project Number: Selcuk University BAP 09102035). Seventy-seven sound molars extracted from patients, mainly for orthodontic, prophylactic, and periodontal reasons, were used in this research. Teeth with hypoplastic areas, cracks, or gross irregularities of the enamel structure were excluded from the study. After the soft tissue remnants and calculus were removed from the teeth, they were cleaned using fluoride-free pumice and a rubber cup. The teeth were then mounted in a 3-cm diameter circular standard mold using autopolymerizing resin (Temdent Classic; Schültz-Dental GmbH, Rosbach, Germany). The long axis of the tooth was parallel to the long axes of the molds, and the teeth were randomly distributed into 11 experimental groups, each containing seven teeth.

### Tooth preparation

Seventy-seven sound molars were circumferentially prepared with 6° convergence, at 4 mm high,<sup>17,18</sup> 5 mm in diameter cylindrical shape, and 2 to 3 mm of occlusal reduction, to ensure a smooth occlusal surface. A 1-mm 360° chamfer with rounded inner angles,<sup>18,19</sup> using the appropriate diamond rotary instruments (Komet, Lemgo, Germany) was used to create complete ceramic crowns with a standard preparation technique (Fig 1A).

### Coping fabrication

Seventy-seven high-precision impressions of the master die were made using a poly(vinyl siloxane) impression material (Zetaplus; Zhermack, Rovigo, Italy) and special impression molds (Fig 1B). Upon completion of the setting time of the impression materials, 77 master working dies were cast with polyurethane-based die material (Alpha Die MF; Schültz-Dental GmbH, Rosbach, Germany) according to the manufacturer's instructions.

All master working dies were coated with two layers of die spacer (Aqua Fit; Renfert GmbH; Hilzingen, Germany), and wax models were created using special Empress wax (Ground Wax; Schuler Dental, Ulm, Germany; Fig 1C). The authors of this study used the press-on technique to fabricate the ceramic copings (IPS e.max; Ivoclar Vivadent AG, Schaan, Liechtenstein), and the IPS e.max ceramic copings (Fig 1D) were fabricated according to the manufacturer's instructions. Airborne particle abrasion was applied to the ceramic copings with Al<sub>2</sub>O<sub>3</sub> (30 to 50 μm) at 0.1 to 0.2 MPa pressure for 3 seconds, and they

were ultrasonically cleaned in water for 10 minutes (Whaledent Biosonic Jr; Whaledent International, New York, NY).

### Luting cements and cementation procedure

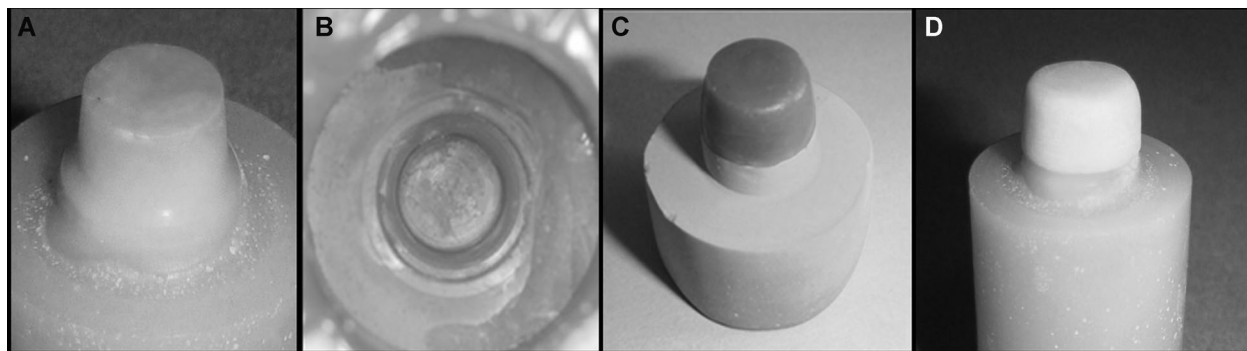
Eight resin-based cements were used in this study: Variolink II, RelyX ARC, Clearfil Esthetic, BisCem, RelyX U100, Panavia EX, Super Bond C&B, and Multilink Automix. Additionally, one resin-modified glass ionomer, one conventional glass ionomer, and one conventional polycarboxylate were used. Their components, manufacturers, and details are listed in Table 1. The luting cements were prepared according to the manufacturers' instructions, mixed, and applied with precision to the bonding surface of the ceramic coping by a single operator (MAM).

### Micro-CT evaluation

A single operator (IT) scanned each specimen using a SkyScan micro-CT scanner (SkyScan 1174 compact desktop X-ray Microtomograph; SkyScan, Kontich, Belgium). The system consisted of a sealed X-ray tube operated at 50 kV. The X-ray source had a power of 40 W, and a precision object manipulator was used to move the specimen translationally in two dimensions and with rotational movement. The specimens were rotated in 1° steps over 360° of rotation, and their sonograms were acquired using a cooled 1.3 megapixel X-ray camera that captured 400 to 450 2D transverse images (or slices; resolution of 1024 × 1024 pixels and an 18 μm slice width; Fig 2). The raw data were further reconstructed to provide an axial cross-section. The cross-sections were collected for each specimen after cone beam reconstruction was complete, and the raw data were converted to 16 bitmapped picture files at a resolution of 1024 × 1024 pixels.

### 3D reconstruction

From the micro-CT examination data, cone beam 3D reconstructions of all cemented ceramic copings were evaluated with the assistance of the Materialise's Interactive Medical Image Control System 13.1 (MIMICS BV, Leuven, Belgium) for analysis based on the gray level differences, cement, tooth, and ceramic coping. On the stack of the raw micro-CT set of slices, the manual regions of interest (ROI) of irregular contour were drawn in the dental cement (Fig 2). The volume of interest (VOI) consisted of a stack of ROIs drawn over 450 cross-sections, while the VOI included the porosity beginning below the ceramic coping and cemento-enamel junction, extending occlusally toward the ceramic coping, excluding both the dental cement and dentin. For the calculation of the porosity volume and area, the images were segmented using a uniform threshold process. MIMICS features extended visualization and segmentation functions based on image density thresholding, where each 3D object is created by growing a threshold region on the entire stack of scans. Each resulting mask (dentin, dental cement, porosity, pulp chamber) is then converted into a 3D file (STL, bilinear and interplane interpolation algorithm) using the MIMICS STL + Module. The porosity was generated as an empty space (no elastic modulus) in the dental cement. The cements and porosities were segmented from each other,



**Figure 1** A. Standardized tooth preparation; B. Impression of prepared tooth; C. Wax model; D. IPS Empress II ceramic copings.

and the porosities were reconstructed separately (Fig 3). After isolation, 3D multiplanar reconstructions were performed for each porosity using the MIMICS function and morphometric tools. The volume and area measurements were conducted with the MIMICS automatic 3D analysis tools.

### Statistical analysis

Descriptive statistics, including the means, standard deviations (SDs), and quartiles, were calculated for each group of teeth. A Kruskal-Wallis one-way ANOVA was used to determine the differences among the groups at a significance level of  $\alpha = 0.05$ . Pairwise comparisons were performed with Bonferroni's adjusted Mann-Whitney U test for each adhesive due to the homogeneity in variance ( $p \leq 0.05$ ).

### Results

The descriptive statistics and quartiles of the porosity volume and surface area for each group are presented in Table 2. When compared with the other tested luting cements, Multilink Automix and Ketac Cem Plus contained the lowest volume and surface area of porosity, after cementation, and this difference was statistically significant ( $p < 0.001$ ). For Variolink II, there was no statistically significant difference in the volume and surface area of porosity when compared to Multilink Automix and Ketac Cem Plus ( $p > 0.05$ ); however, the volume and surface area of the porosity of the other tested luting cements was significantly greater than Multilink Automix and Ketac Cem Plus ( $p < 0.001$ ), while there were no significant differences among the three cements ( $p > 0.05$ ). Figure 4 shows reconstructed 3D images of the tested materials after cementation. In these reconstructed images, the transparent cement matrix clearly shows the presence of porosity.

Ketac Cem Plus and Multilink Automix showed the lowest porosity based on volume and area in all of the materials tested. The porosities were localized to the middle and occlusal parts of the ceramic copings, and the voids were inconsistent with each other (Fig 4A). Figure 4B shows typical images for Ketac Cem, which were of cement mixed both mechanically and by hand. Ketac Cem showed that numerous large porosities had been incorporated into the ceramic copings' occlusal section. Furthermore, there were small porosities on the cervical part

of the ceramic copings. For RelyX U100, the ceramic copings detected significantly more porosity in the occlusal area, but those porosities were not diffused, and they occupied a limited area (Fig 4C). Multilink Automix contained minimal voids of the tested materials, and the gaps were located on the occlusal part of the ceramic copings (Fig 4D). RelyX ARC demonstrated that diffuse and large porosities had been incorporated onto the occlusal part of the ceramic copings (Fig 4E), while 3D Variolink II images demonstrated few and small gaps on the occlusal part of the ceramic coping (Fig 4F).

Durelon contained only small porosities, which were widely scattered, and there was no connection between them (Fig 4G). Typical images for Panavia EX showed very large and extensive porosities, most being located on the occlusal part of the ceramic copings (Fig 4H). BisCem revealed that many large porosities had been incorporated into the occlusal and middle sections of the ceramic copings, and small porosities were found on its cervical section (Fig 4I). Three-dimensional images for Clearfil Esthetic showed that both linear porosities, especially in the cervical margin, and large porosities were found on the occlusal part of the ceramic copings (Fig 4J). Finally, Super Bond C&B revealed that many large, scattered bubbles had been incorporated, especially on the ceramic copings' cervical area, which were dispersed (Fig 4K).

### Discussion

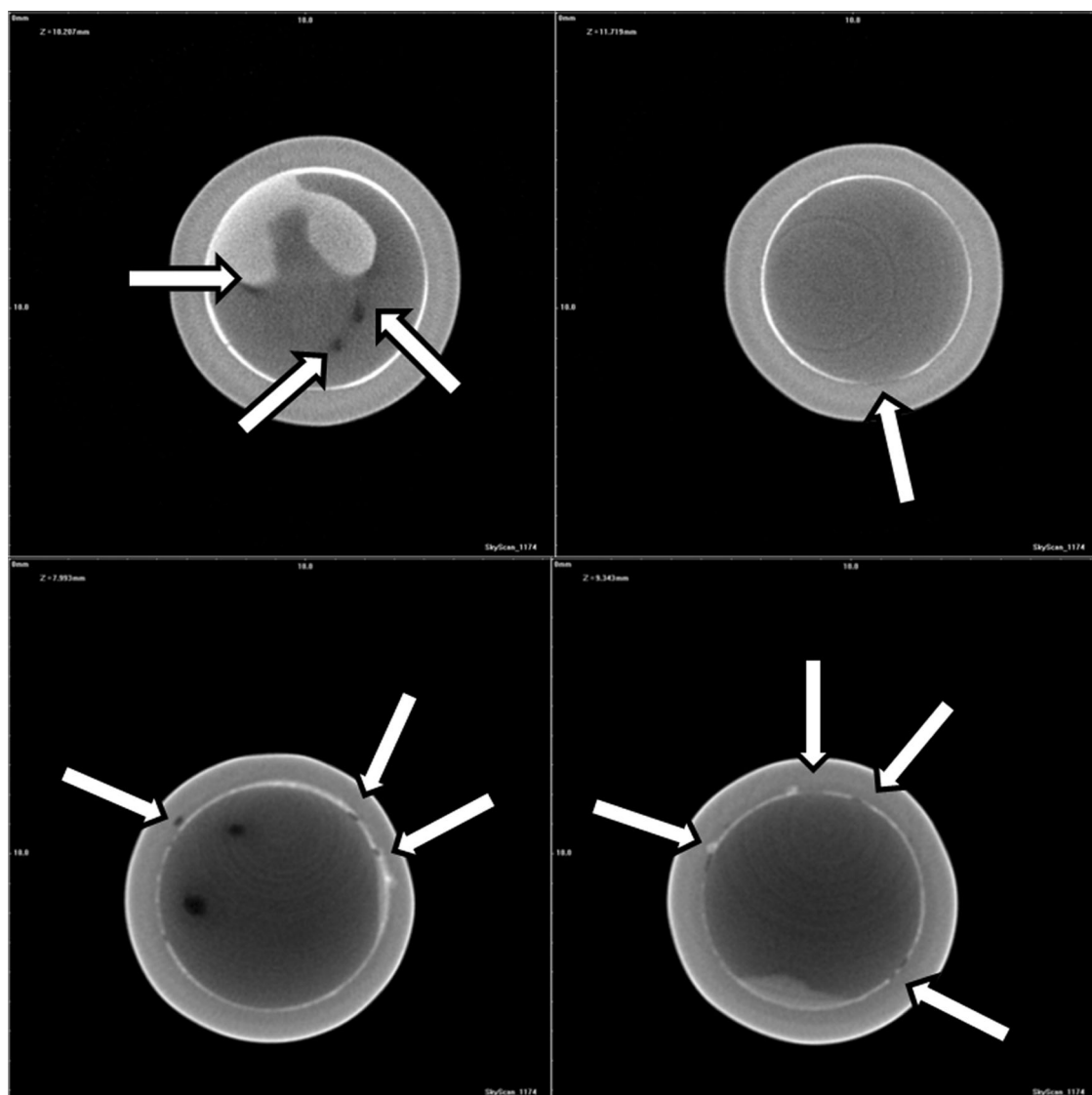
Micro-CT is not used in clinical practice. Moreover, from a clinical point of view, there are limitations regarding the correlation between in vitro testing and clinical usage tests; however, in vitro micro-CT analysis is important in understanding and evaluating the internal structure of dental cement after the cementation procedure under fixative restorations. This study's results demonstrate that specimens produced by hand mixing had significantly greater porosity than the results produced by automatic mixing. Thus, the null hypothesis of this study was rejected.

Ceramic copings were used in this study because dental ceramics are chemically stable, biocompatible, and corrosion resistant.<sup>8</sup> The finish line of the prepared tooth can be placed at the free gingival margin without compromising the tooth's esthetic appearance, while avoiding violation of the biological

**Table 1** Cements used

Cement type	Brand name	Ingredients <sup>Y</sup>	Luting agent mixing	Manufacturer and lot. number, polymerization type
Resin modified glass ionomer	Ketac Cem Plus	Water (10% to 15%), HEMA (15% to 20%), silica (5%), 4-Dimethylamino-Benzeneethanol (1%)	Mix base: 1 and catalyst paste: 1 for 20 s	3M ESPE, St. Paul, MN, 56930, self cure
Glass ionomer	Ketac Cem	LIQUID: Water (80% to 90%), tartaric acid (10% to 20%); POWDER: Glass (80% to 85%), polyethylene carbonic acid (10% to 20%)	Mix liquid: 2 and powder: 1 for 60 s	3M ESPE, St. Paul, MN, 313132, self cure
Resin cement	RelyX U100	BASE: TEGDMA (10% to 20%), silica (1% to 5%), methacrylate phosphoric acid esters (15% to 25%), glass (55% to 65%); CATALYST: dimethacrylate (20% to 30%), glass (55% to 65%), silica (1% to 5%)	Mix base: 1 and catalyst paste: 1 for 20 s, light cure for 20 s from each side	3M ESPE, St. Paul, MN, 335294, self cure
Resin cement	Multilink Automix	DMA (22% to 26%), HEMA (6% to 7%), benzoylperoxide (1%), filler cont. (65% to 70%)	Mix base: 1 and catalyst paste: 1 for 20 s	Ivoclar Vivadent AG, Schaan, Liechtenstein, L10132, self cure
Resin cement	RelyX ARC	BASE: TEGDMA (10% to 20%), Bis-GMA (10% to 20%), DMA (1% to 10%), filler (60% to 70%); CATALYST: TEGDMA (10% to 20%), Bis-GMA (10% to 20%), DMA (1% to 10%), benzoylperoxide (1%), filler cont (55% to 65%)	Mix base: 1 and catalyst paste: 1 for 20 s, light cure for 20 s from each side	3M ESPE, St. Paul, MN, 3415, dual cure
Resin cement	Variolink II	Bis-GMA (10% to 14%), TEGDMA (5% to 7%), UDMA (5% to 7%), benzoylperoxide (1%), filler cont (73%)	Mix base: 1 and catalyst paste: 1 for 10 s, light cure for 40 s from each side	Ivoclar Vivadent AG, Schaan, Liechtenstein, K35423, dual cure
Polycarboxylate	Durelon	LIQUID: acrylic acid, polymers (30% to 50%); POWDER: zinc oxide (80%)	Mix liquid: 1 and powder: 1 for 30 s	3M ESPE, St. Paul, MN, 338027-338277, self cure
Resin cement	Panavia EX	POWDER: Silica; barium sulfate; LIQUID: 10-methacryloxydecyl dihydrogen phosphate, hydrophobic dimethacrylate, benzoyl peroxide	Mix liquid: 2 and powder: 1 for 60 s	Kuraray Medical Inc. Okayama, Japan, 41298, self cure
Resin cement	Bis Cem	HEMA (<10%), TEGDMA (<25%), filler cont. (<85%)	Mix base: 1 and catalyst paste: 1 for 10 s, light cure for 30 s from each side	Bisco, Schaumburg, IL, 0900008609, dual cure
Resin cement	Clearfil Esthetic	BisGMA (<10%), TEGDMA (<8%), filler cont. (<85%)	Mix base: 1 and catalyst paste: 1 for 20 s, light cure for 20 s from each side	Kuraray Medical Inc., Okayama, Japan, 41148, dual cure
Resin cement	Super Bond C&B	PMMA (0% to 50%), metal oxides (0% to 50%)	Mix monomer: 4 and catalyst: 1 for 10 s	Sun Medical, Shiga, Japan, TL1, dual cure

<sup>Y</sup> Bis-GMA: bisphenol A diglycidyl methacrylate; UDMA: 2-hydroxyethylmethacrylate; PMMA: polymethylmethacrylate; TEGDMA: triethylene glycol dimethacrylate; decamethylen-DMA: decamethylen-dimethacrylate; second: s.



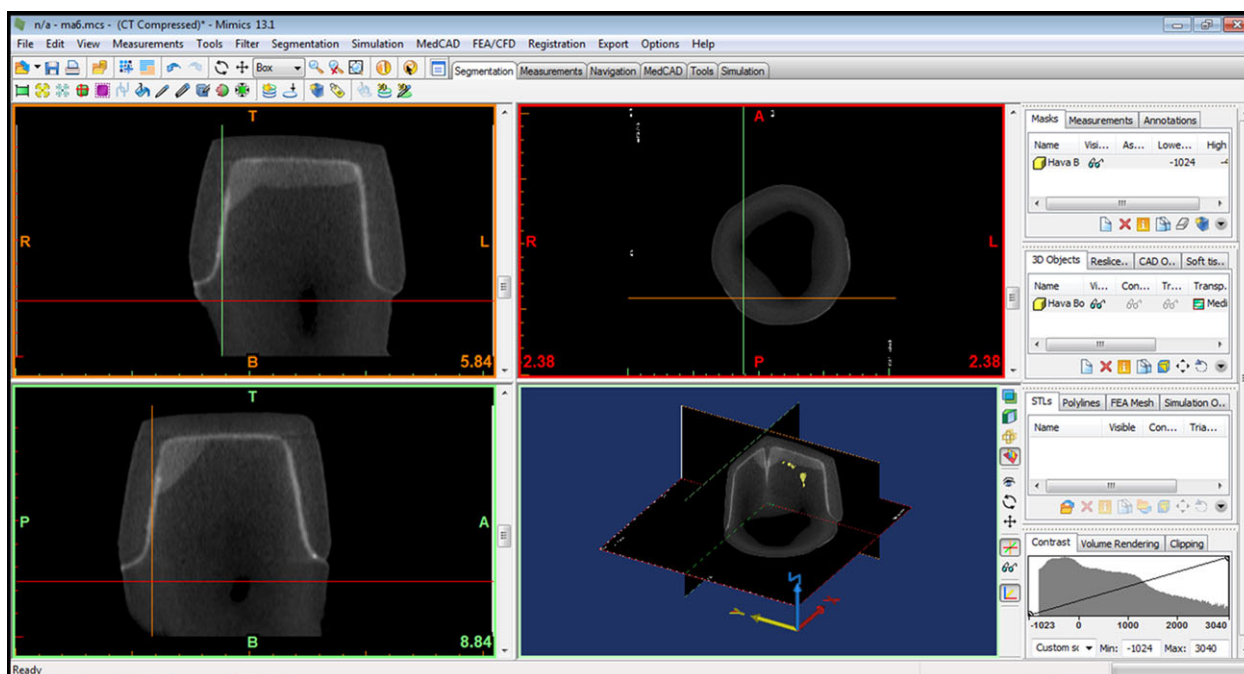
**Figure 2** Two-dimensional transversal images (or slices). The ceramic coping and cements appear light gray, dentin appears dark gray, and porosity appears black. Arrows indicate areas of porosity in the luting cements.

width.<sup>12</sup> In addition, IPS e.max ceramic copings are easier to differentiate with the use of micro-CT. Generally, in the prosthodontic literature, a stainless steel model simulating the prepared abutment is constructed to replicate natural teeth.<sup>11,13</sup> There are two main disadvantages to the stainless steel preparation model: first, detailed and precise micro-CT evaluation is not possible due to phase contrast and ring artifacts.<sup>12</sup> Second, different materials and techniques are used in cementation, and different precementation surface treatments on both the tooth and restoration are required for different types of restorative material. As a result, these procedures may affect the quantity and localization of porosities. In this study, the molars were naturally prepared using the standard preparation method.

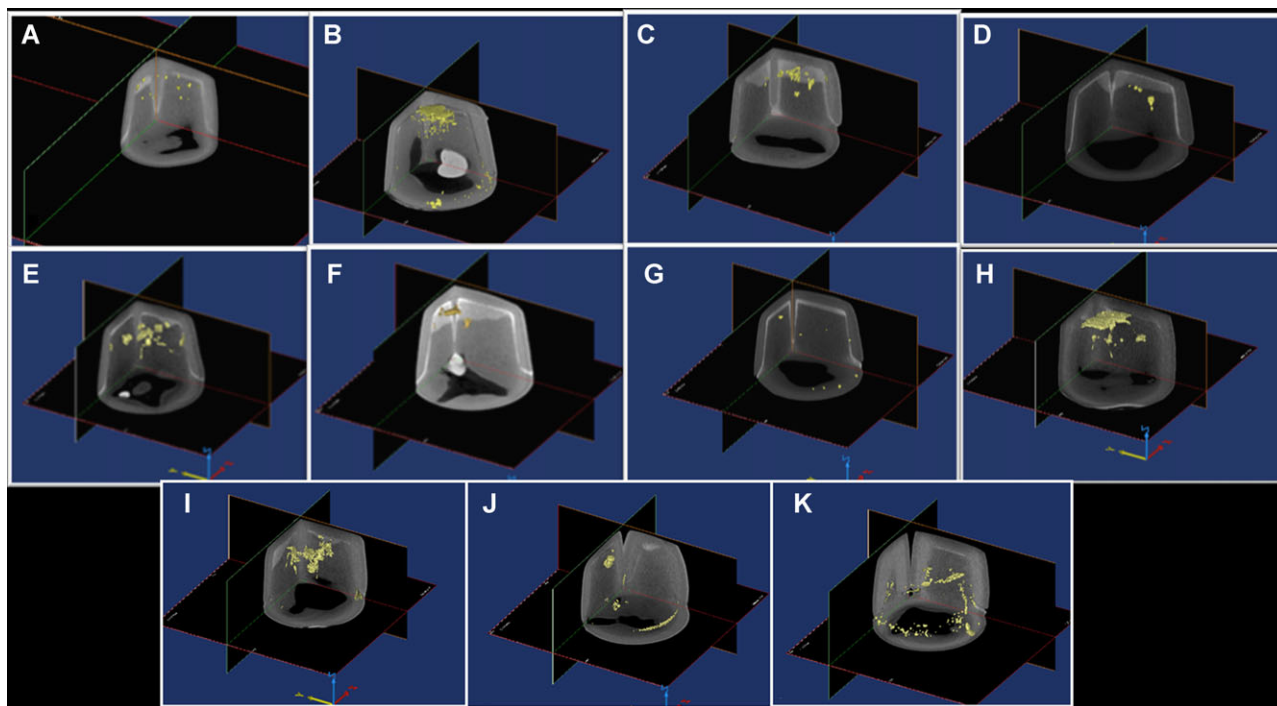
Borba *et al*<sup>11</sup> used metal preparation abutment models instead of natural teeth to evaluate the internal and marginal gap fit

using micro-CT. According to Borba *et al*,<sup>11</sup> it “is not possible to perform an accurate analysis in situations where insufficient radiographic contrast exists.” Therefore, to improve contrast between the metal die, ceramic restoration, and internal gap, the scanning procedure was performed without cementation. The main limitations of the Borba *et al*<sup>11</sup> study do not take into consideration the influence of the luting procedure, the cement type in the gap width, and not using a 3D model. The results of this study demonstrate that, when the proper micro-CT scanning procedure was chosen with natural teeth and the appropriately chosen ceramic restoration was used, the cement gap, restoration/tooth surface interface, and internal structure of the luting dental cement could be examined in a 3D model. Natural teeth make the tooth structure/restoration interface and the internal structure of dental cements more visible for performing





**Figure 3** Three-dimensional reconstruction of the cemented ceramic coping with MIMICS 13.1 and calculation of porosity volume and surface area in cement materials.



**Figure 4** Reconstructed porosity images in tested cements. A. Ketac Cem Plus; B. Ketac Cem; C. RelyX U100; D. Multilink Automix; E. RelyX ARC; F. Variolink II; G. Durelon; H. Panavia EX; I. BisCem; J. Clearfil Esthetic; K. Super Bond C&B.

**Table 2** Comparison of porosity volume and area in cements

	Volume (mm <sup>3</sup> )			Area (mm <sup>2</sup> )		
	Mean	SD	Mann-Whitney U <sup>§</sup>	Mean	SD	Mann-Whitney U <sup>§</sup>
Ketac Cem Plus	0.22	0.21	A	4.32	3.71	A
Ketac Cem	0.68	0.86	B	15.97	16.08	B
RelyX U100	0.70	0.67	B	14.35	10.64	B
Multilink Automix	0.11	0.08	A	1.63	1.31	A
RelyX ARC	0.88	1.11	B	15.45	10.45	B
Variolink II	0.34	0.38	AB	6.47	5.10	AB
Durelon	0.42	0.62	B	15.08	19.94	B
Panavia EX	0.92	0.90	B	13.80	11.23	B
Biscem	1.13	0.82	B	16.98	10.04	B
Clearfil Esthetic	0.71	0.81	B	11.93	10.59	B
Super Bond C&B	1.33	0.76	B	26.11	14.19	B

§Means of the same letter are not significantly different at  $\alpha = 0.05$ . SD: standard deviation.

the 3D model reconstruction, enabling the authors to analyze the volume, localization, and area exhibiting porosities. Studies conducted by Seo *et al*<sup>14</sup> and Pelekanos *et al*<sup>9</sup> applied the micro-CT technique to evaluate the fit of the ceramic crowns, and these authors recommended this method as a useful tool.

In many ways, the degree of bonding between the restoration and dentin determines the overall success of fixed restorations. Traditionally, light or electron microscopy and other specialized methods are used to evaluate the tooth structure/restoration interface and cement gap; however, most of these methods are destructive and can only be applied after preparing experimental specimens by cutting the tooth into halves or a series of thin sections. For this reason, these methods do not permit the dynamic investigation of peculiarities that develop at the restoration/dentin interface. In short, a novel approach to the nondestructive evaluation of cement dentin adhesion is required.<sup>15</sup> Micro-CT is a nondestructive method of analysis that allows high resolution of the dental cement, where porosities can be found between the prepared dentin and the ceramic coping. Therefore, in this study, the localization and volume porosities inside the luting dental cement could be evaluated in the vertical, horizontal, and transversal planes, providing a more realistic representation of the internal structure of luting cements placed between the prepared dentin and the restoration.

Another method that measures porosities inside dental cement is mercury intrusion porosimetry (MIP). MIP is a technique designed to assess porosity based on the behavior of nonwetting liquids around inundated porous objects. Mercury does not spontaneously move into pores, but it can be forced into pores. With increased applied pressure, the mercury penetrates smaller pores; therefore, the minimal detectable pore diameter using MIP is the one obtained at maximal working pressure.<sup>16</sup> MIP is very sensitive, and it can be detected in pores smaller than 20 nm.<sup>16</sup> However, MIP cannot detect closed and blind pores, except in open porosities.<sup>18</sup> This method does not provide information about the localization and connection of the porosities. However, Milutinovic-Nikolic *et al*<sup>16</sup> showed that the majority of pores in many types of cement are below the 0.1 to 18  $\mu\text{m}$  sections by micro-CT used in this study,

which seems relatively large; however, this condition depends on the micro-CT scanner limits. Further studies may be planned with advanced micro-CT scanner models. There is no reported 0% or fixed level of porosity of dental cements in the literature. For this reason, we did not use a control group; instead we compared the porosity measurements among the tested groups.

The disadvantage of the micro-CT is its low resolution when compared to using an electron or optical microscope. Furthermore, considering that the images result from radiation, there may be artifacts from refraction. Various materials having different values of X-ray absorption hinder the definition of the outlines between these materials.<sup>9</sup> It is very problematic to separate the lines between two materials with the same X-ray absorption coefficients when they are in contact. This condition should be evaluated when using the micro-CT technique; however, this study demonstrated that micro-CT was very useful for developing a standard method to examine the number of porosities and where they were located under ceramic restorations *in vitro*.

Nomoto *et al*<sup>10</sup> evaluated the effects of mixing methods and porosity formation in five glass ionomer cements using micro-CT. These authors suggested that mixing method has a significant effect on the formation of porosities. For luting cement, mechanical mixing produced significantly greater porosity. They concluded that hand mixing is preferred for luting cements (low-viscosity cements), while this is not applicable for restorative cements (high-viscosity cements); however, they used cylindrical specimens, not natural teeth or ceramic copings.<sup>10</sup> Nomoto *et al*<sup>10</sup> concluded that this research design would better mimic clinical conditions and be more realistic than the other methodologies. Milutinovic-Nikolic *et al*<sup>16</sup> compared the open porosity and pore size distributions of zinc phosphate, polycarboxylate, glass ionomer, and resin-based cements using MIP. They demonstrated that polycarboxylate cement exhibits the highest porosity, and that zinc phosphate and glass ionomer cement presented smaller pore volumes when compared to the polycarboxylate cement. The resin-based cement showed the least porosity. The results of this study confirm the findings

of Milutinovic-Nikolic *et al*,<sup>16</sup> who also demonstrated that Multilink Automix and Ketac Cem Plus had the lowest porosity area and volume, whereas Super Bond C&B had the greatest values.

Ketac Cem, Durelon, Panavia EX, and Super Bond C&B cements come in liquid and powder forms and are prepared by manual mixing; however, Ketac Cem Plus, RelyX U100, RelyX ARC, Variolink II, Multilink Automix, BisCem, and Clearfil Esthetic are two-paste systems. The differences between hand and automatic mixing probably resulted from differences in the products' viscosities. It appears that hand mixing the material more readily causes air inclusions, when a type of "froth" is formed during the mixing process. The automatic mixing procedure helps to avoid these inclusions and may also cause some porosities to collapse.<sup>19</sup> The more viscous the material, such as resin-modified glass ionomer cement, combined with a lower probability of air inclusions during automatic mixing, has been reported to produce the most favorable mechanical properties.<sup>19</sup> Furthermore, increased mechanical mixing time does not appear to speed up the setting time of the cements. Excessively slow mixing speeds will result in unmixed powder, which may adversely affect the mechanical properties of the set cement. Moreover, particles of liquid-powder cement are manufactured in micrometric dimensions, but two-paste system cements are manufactured using nanometric dimensions.<sup>1</sup> The authors of this study speculate that differences in particle size may contribute to the formation of porosities.<sup>1</sup>

There is no linear correlation between the volume and area for porosity according to our results. Although Ketac Cem, RelyX U100, RelyX ARC, Durelon, Panavia EX, Clearfil Esthetic, and BisCem have minimal porosity volumes, the porosities are scattered over a wide area; however, Ketac Cem Plus, Multilink Automix, and Variolink II have not only minimal porosity volume, but also porosities collected in a limited area. These situations were confirmed by 3D reconstruction images. Consequently, the 3D evaluation of porosities' location inside the dental cement is very critical for clinical success, in addition to the compilation of numerical data.

The 3D micro-CT modeling of Ketac Cem Plus, RelyX U100, Multilink Automix, RelyX ARC, Panavia EX, and BisCem cements demonstrated that porosities are localized in the middle and occlusal parts of a ceramic restoration. Ketac Cem, Durelon, Clearfil Esthetic, and Super Bond C&B cements showed that porosities surrounded the cervical part of the restoration, and these findings should be meticulously evaluated for microleakage, bonding failure, and long-term stabilization of the restoration. Further studies should also be planned to assess these topics. The removal of the porosities from the complete crown will facilitate the escape of cement from the crowns and allow for a more complete seating.<sup>20,21</sup>

Problems can ensue, however, in preparations with unusually long, nearly parallel axial walls. According to Shillingburg *et al*,<sup>20</sup> the most effective venting is provided by drilling a hole in or near the occlusal surface, but this method leaves a defect in the crown after cementation. Shillingburg *et al*<sup>20</sup> recommended different methods for sealing the vent hole, such as using filling materials, metal screws, and cemented plugs. Thus, the elimination of porosities can be achieved by creating an internal escape

channel in the form of an unoccupied vertical groove in the axial wall of the tooth preparation or in the internal surface of the restoration; however, venting does not eliminate porosities incorporated into the cement during mixing or manufacture, but does provide a path for entrapped air to escape during seating. There have been no clinical studies looking at either restoration longevity or success as it relates to luting porosities. Depending on the materials used, further investigations must be carried out to assess the relationship between porosities and mechanical tensile stress, and the impact on the clinical performance of restorations. Additional studies should be planned with regard to the clinical repercussions associated with manipulation, preparation, and type of luting cements on the basis of the incidence of complications encountered. Furthermore, research efforts should also focus on assessing the removal of porosities from the restoration.

## Conclusion

Within the limitations of the present experimental approach, the following can be concluded: liquids and powders prepared by manually mixing cement were found to form greater porosity.

## References

1. O'Brien WJ: Dental Materials and their Selection, Vol 9 (ed 3). Chicago, Quintessence, 2002, pp. 132-155
2. Oysaed H, Ruyter IE: Water sorption and filler characteristics of composites for use in posterior teeth. *J Dent Res* 1986;65:1315-1318
3. Sideridou I, Tserki V, Papanastasiou G: Effect of chemical structure on degree of conversion in light-cured dimethacrylate-based dental resins. *Biomaterials* 2002;23:1819-1829
4. Feilzer AJ, De Gee AJ, Davidson CL: Curing contraction of composites and glass-ionomer cements. *J Prosthet Dent* 1988;59:297-300
5. Ciucchi B, Bouillaguet S, Delaloye M, *et al*: Volume of the internal gap formed under composite restorations in vitro. *J Dent* 1997;25:305-312
6. Condon JR, Ferracane JL: Reduced polymerization stress through non-bonded nanofiller particles. *Biomaterials* 2002;23:3807-3831
7. Barralet JE, Gaunt T, Wright AJ, *et al*: Effect of porosity reduction by compaction on compressive strength and microstructure of calcium phosphate cement. *Biomed Mater Res* 2002;63:1-9
8. Fleming GJP, Addison O: Adhesive cementation and the strengthening of all-ceramic dental restoration. *J Adhes Sci Tech* 2009;23:945-959
9. Pelekanos S, Koumanou M, Koutayas SO, *et al*: Micro-CT evaluation of the marginal fit of different In-Ceram alumina copings. *Eur J Esthet Dent* 2009;4:278-292
10. Nomoto R, Komoriyama M, McCabe JF, *et al*: Effect of mixing method on the porosity of encapsulated glass ionomer cement. *Dent Mater* 2004;20:972-978
11. Borba M, Cesar PF, Griggs JA, *et al*: Adaptation of all-ceramic fixed partial dentures. *Dent Mater* 2011;27:1119-1126
12. Stock S: Micro CT in practice. In Stock SR (ed): *Micro Computed Tomography: Methodology and Applications*, Vol 5 (ed 1). Boca Raton, FL, Taylor & Francis, 2009, pp. 85-108
13. Webber B, McDonald A, Knowles J: An in vitro study of the compressive load at fracture of Procera AllCeram crowns with



- varying thickness of veneer porcelain. *J Prosthet Dent* 2003;89:154-160
14. Seo D, Yi Y, Roh B: The effect of preparation designs on the marginal and internal gaps in Cerec3 partial ceramic crowns. *J Dent* 2009;37:374-382
  15. Desinova LA, Maev RG, Leontijev VK, et al: Study of the adhesion between dental cement and dentin using a nondestructive acoustic microscopy approach. *Dent Mater* 2009;25:557-565
  16. Milutinovic-Nikolic AD, Medi VB, Vukovic ZM: Porosity of different dental luting cements. *Dent Mater* 2007;23:674-678
  17. Goodacre CJ, Campagni WV, Aquilino SA: Tooth preparations for complete crowns: An art form based on scientific principles. *J Prosthet Dent* 2001;85:363-376
  18. Song HY, Yi YJ, Cho LR, et al: Effects of two preparation designs and pontic distance on bending and fracture strength of fiber-reinforced composite inlay fixed partial dentures. *J Prosthet Dent* 2003;90:347-353
  19. Fleming GJ, Kenny SM, Barralet JE: The optimisation of the initial viscosity of an encapsulated glass-ionomer restorative following different mechanical mixing regimes. *J Dent* 2006;34:155-163
  20. Shillingburg HT, Hobo S, Whitsett LD, et al: *Fundamentals of Fixed Prosthodontics* (ed 3). Chicago, Quintessence, 1997, pp. 401-405
  21. Van Nortwick WT, Gettleman L: Effect of internal relief, vibration, and venting on the vertical seating of cemented crowns. *J Prost Dent* 1981;45:395-399