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Marginal Adaptation and Porosity of a Novel MTA Brand Applied as Root-End Filling Material: A Micro-CT Study

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Featured Application: This is the first investigation to quantitatively assess the porosity of a novel MTA brand, Harvard MTA, in terms of all three of its aspects (interfacial, internal, and total) through the use of micro-computed tomography. When applied as a retrofilling, the experimental results demonstrated excellent marginal adaptability and filling capacity for this calcium silicate cement. These findings could be beneficial to clinicians in selecting the most appropriate root-end filling biomaterial for endodontic surgery. Furthermore, they could be helpful for other endodontic applications of Harvard MTA Universal.

Abstract: Marginal adaptation and internal porosity characteristics of root-end filling materials are important factors determining their clinical performance. The aim of this study was to quantitatively evaluate the marginal adaptation to radicular dentin (interfacial void volume) and internal porosity volume of a novel mineral trioxide aggregate brand using micro-CT analysis. Ten extracted upper central incisors were selected, instrumented, and obturated. Roots were resected at the apical 3 mm, and root-end cavities were prepared ultrasonically and filled with Harvard MTA. SkyScan 1272 micro-CT equipment was used to scan the specimens at a resolution of 6 µm, and three-dimensional images were reconstructed. All volumetric porosity parameters of the tested material were calculated in absolute (mm^3) and relative values (%), as follows: open porosity volume (OPV), closed porosity volume (CPV), and total porosity volume (TPV). The mean OPV and OPV% found for Harvard MTA were 0.0268 mm^3 and 0.91%, respectively. The mean CPV and CPV% were 0.0283 mm^3 and 0.94%, respectively. The TPV and TPV% were 0.0569 mm^3 and 1.85%. There was no significant difference between the OPV% and CPV% ($p < 0.05$). In conclusion, when applied as a retrofilling material, Harvard MTA exhibited excellent marginal adaptation to the dentin with minimal interfacial voids and internal microporosity. Therefore, this new calcium silicate brand may be considered an efficient alternative to conventional products.

Keywords: Harvard MTA; calcium silicate cement; marginal adaptation; porosity; micro-CT

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1. Introduction

Mineral trioxide aggregate (MTA) was the first bioactive endodontic cement introduced in practice in 1993 by Torabinejad et al. [1] It has been a revolutionary material that opened the door to a new era for hydraulic cements, also known as calcium silicate cements (CSCs). This class of biomaterials has a wide range of applications in endodontics. Their extended usage includes dressing over pulpotomy, pulp capping, apexification, orthograde or retrograde apical plug, regenerative procedures, repair of root perforation and root resorptions, root canal sealing, etc. [1,2]. Due to their unique physicochemical and biological properties, CSCs have currently been considered an excellent root-end filling material [2–5].

However, the early MTA products exhibited some drawbacks and usage limitations: long setting time, poor handling characteristics making manipulation difficult, discoloration potential, washout effect, etc. [1]. A number of novel bioactive cements have been developed and brought into the dental market in recent years in an effort to overcome these shortcomings. They are referred to as bioceramics, and it is believed that they have superior characteristics to conventional MTA products [6,7].

One of the latest restorative brands of this group of biomaterials is Harvard MTA Universal. This repair cement is commercially available as a hand-mix formula or in predosed capsules. The manufacturer claims that this MTA-based material is biocompatible, possesses outstanding physical properties, and does not require moisture during the setting process, allowing for the following clinical step to be completed after 5 min [8]. However, only limited scientific evidence has been reported in the literature considering its properties to date. The chemical composition of Harvard MTA was determined by X-ray powder diffraction analysis, which indicated the presence of two distinct forms of calcium silicates in its formulation: 75 wt% merwinite and 20 wt% hatrurite, and 5 wt% bismuth oxide as a radiopacifier. In contrast, hatrurite constitutes 90 wt% of the mineral composition in ProRoot MTA plus 10 wt% bismuth oxide [9].

When compared to ProRoot MTA, Harvard MTA Universal showed a significantly higher pH value (12.5) and a lower solubility (0.32%) in phosphate-buffered saline solution; however, after a 14-day period of storage, it exhibited significantly lower calcium ion release values [9]. The cement showed a much lower push-out bond strength than Biodentine in terms of its dislodgement resistance, although there was no statistically meaningful difference with ProRoot MTA [10,11]. As for its biological properties, it was found that ProRoot MTA and MTA Flow showed better biocompatibility than Harvard MTA [12].

As can be seen from this brief review of the available literature, the properties of Harvard MTA have not yet been thoroughly investigated. There are almost no studies on the sealing capacity of this new MTA brand, and its marginal adaptation, in particular, has not been investigated volumetrically so far. In light of the paucity of scientific evidence on this topic, the present study was designed to quantitatively assess the marginal adaptability and interior microporosity of this innovative biomaterial applied as root-end filling material using three-dimensional micro-computed tomography (micro-CT) analysis.

2. Materials and Methods

2.1. Sample Construction

A total of 10 freshly extracted, human, intact upper central incisors were utilized in this study, obtained from the Department of Oral and Maxillofacial Surgery. On the basis of the initial radiographic and clinical evaluation, suitable teeth were chosen. The inclusion criteria were as follows: (1) single straight root and canal; (2) patent canal with an apical diameter of at least ISO 0.15 K file; (3) completely formed root; and (4) intact pulp chamber. Immature teeth with open apices, teeth presenting root fractures, cracks, root caries, internal or external resorption, root curvature, calcified root canals, and previous root canal treatment were excluded.

Following extraction, the teeth were left in 10% buffered formalin for two weeks. The remaining soft tissues and calculus were removed manually and ultrasonically. The teeth were subsequently cleaned and disinfected in a mixture of 3% hydrogen peroxide and 2.6% sodium hypochlorite and rinsed under tap water. Lastly, prior to the experiment's performance, they were maintained in a normal saline solution containing 0.2% thymol.

2.2. Root Canal Preparation

Root canal preparation of the teeth was performed using rotary endodontic NiTi instruments (ProTaper Gold), and root canals were filled with corresponding calibrated gutta-percha points (Dentsply Sirona, Ballaigues, Switzerland), according to the technique described in our previous study [13].

2.3. Root-End Cavity Preparation

In order to simulate apicoectomy, the apical section of the roots (3 mm) was excised under continuous water cooling using a high-speed Lindemann surgical carbide bur (Dentsply Sirona, Ballaigues, Switzerland). Following root-end resection, retrocavities were prepared ultrasonically along the root canal. A piezoelectric device, Suprasson P5 Booster (Acteon Satelec, Mérignac, France), was used for this purpose, with the relevant Satelec diamond-coated universal micro retrotip P14D with constant irrigation. The cavity dimensions were standardized to a depth of 3 mm and a diameter of 1 mm with the help of a graduated William periodontal probe (R&S Dental Products, Paris, France) and a hand plugger with an appropriate diameter (Dentsply Maillefer, Tulsa, OK, USA).

2.4. Root-End Cavity Filling

The root-end cavities were filled with Harvard MTA Universal HandMix (Harvard Dental International GmbH, Hoppegarten, Germany). The cement was prepared manually on a glass slab using a metal spatula, in accordance with the manufacturer's instructions, as the powder/liquid ratio by weight was 2.6/1.0. After mixing, Harvard MTA was inserted into the retrocavity using a MAP One syringe (Micro-apical Placement System, Produits Dentaires SA, Vevey, Switzerland), according to the technique described in our previous study [13]. All procedures were performed by one experienced endodontist wearing binocular magnifying lenses Labo-clip (Eschenbach, Nürnberg, Germany) with $\times 2.5$ magnification. The quality of the MTA root-end fillings was checked radiographically. Finally, the specimens were stored in a closed container and incubated in 100% humidity at 37 °C for 24 h.

2.5. Micro-CT Scans and Analysis

The specimens were scanned with high-resolution micro-CT equipment, SkyScan 1272 (Bruker-microCT, Kontich, Belgium). The following system settings were used for the scanning process: a voltage of 100 kV, a current of 100 mA, a 0.4 rotation step, and a 1406 ms exposure time. The procedure was performed at an isotropic resolution of 6 μm using a 0.11 mm copper filter. The teeth were placed in closed Eppendorf tubes with a moist cotton piece at the bottom to prevent dentin desiccation during the 90 min scan. Images of the specimens were reconstructed using a ring artifact reduction factor of 2 and beam hardening correction of around 5% with NRecon v. 1.7.4.2 software (Bruker Micro-CT).

CTAn (version 1.20.8) and CTVol software (v. 2.3.2.0; Bruker Micro-CT, SkyScan, Belgium) were used for the three-dimensional (3D) reconstruction, quantification of the root-end cavity and filling material volume, the calculation of the material porosity, and the relevant volumetric analysis. The 3 mm thick apical portion of the resected root was chosen as the region of interest (ROI). In order to measure the volume of the gap at the root dentin-to-filling material interface, the volume of interest (VOI) was determined as a cylindrical area with a length of 3 mm that included only the root-end cavity.

Porosity was determined by segmentation within the ROI. Grayscale thresholds were defined semi-automatically in order to separate the different "phases": root dentin, cavity borders, material, interfacial gaps, and inner pores. Due to the heterogeneous structure of the filling material and the large absorption difference between the dots in the cement and the rest of the 3D image, the grayscale range was so selected that the dots were slightly overexposed. Densities ranging from 80 to 255 were specified for the filling material and 80–255 for the voids (pores). The established threshold gray level thus enabled the detection of pores inside the VOI that were smaller than 5 μm. A binarizing method (i.e., black-and-white images) was also applied for images in the VOI in order to facilitate the quantification process. Micro-CT scans, image reconstructions, and volumetric measurements were performed by one experienced operator.

The cavity volume (Vc) and the root-end filling material volume (Vm) were measured in mm^3. Then the following parameters were calculated: (1) the volume of the interfacial gaps and voids present in the material-to-dentin wall interface, defined as open porosity volume for brevity (OPV); and (2) the volume of micropores within the material, defined as closed porosity volume (CPV). The quantities of both the internal and interfacial porosity fractions were measured separately and as the total amount (TPV). They were calculated as absolute values in mm^3 and relative values in percentages.

To assess the volume of interfacial open pores (OPV), the sum of the filling material volume (Vm) itself, including closed pores (CPV), was subtracted from the cavity volume (Vc). Then the total porosity volume was calculated as a sum of OPV and CPV. Subsequently, the relative values of those parameters (OPV% and CPV%) were computed using the following formulas (Equations (1) and (2)):

$$\mathbf{OPV\%} = \frac{OPV}{Vc} \times 100 \tag{1}$$

and

$$\mathbf{CPV\%} = \frac{CPV}{Vm + CPV} \times 100 \tag{2}$$

Ultimately, the sums of OPV + CPV and OPV% + CPV% were utilized to calculate the total porosity volume and percentage.

2.6. Statistical Analyses

All data were processed and analyzed with IBM SPSS Statistics 25.0 (IBM SPSS Statistics for Windows, SPSS Inc., Chicago, IL, USA). The following statistical methods were used: descriptive statistics, the Shapiro–Wilk test, and the paired samples t-test. The normality check of the data was performed using the Shapiro–Wilk test. It revealed that the evaluated characteristics, i.e., open pores and closed pores (in volume and percentage), were normally distributed, so for both pairs, a parametric test was applied: paired samples t-test. The significance level was set at 0.05, and a p-value less than 0.05 ($p < 0.05$) was considered statistically significant.

3. Results

Overview of Results

The segmentation results and 3D micro-CT images revealed an excellent view of the root dentin, retrofilling material, and voids within the VOI at the specified gray values. In general, a noticeable gap at the dentin-to-material interface was not detected visually. Actually, the interface could more accurately be defined as an imaginary space represented by separate open pores that were not interconnected. A typical gap was found only in one specimen at a depth of approximately 3 mm. All samples showed the presence of micropores existing inside the structure of the retrograde filling.

Descriptive statistics (mean values, CI, SD, etc.) and volumetric analysis of open (interfacial), closed (internal), and total porosity exhibited by the Harvard MTA retrograde filling, in mm^3 and percentage, are summarized in Table 1 and presented graphically in Figure 1. Figures 2–6 display representative original images acquired from Harvard MTA in three planes, binarized pictures of transversal cross sections, and a three-dimensional reconstruction of the porosity in the VOI.

Table 1. Descriptive statistics of the porosity volume exhibited by Harvard MTA Universal.

Characteristics	Mean	SEM	95% CI of Mean	SD	Min	Max
OPV (μm^3)	0.0268 ^{a}	0.0028	(0.0206–0.0330)	0.0087	0.0152	0.0448
OPV (%)	**0.9080** ^{b}	0.0872	(0.7108–1.1052)	0.2757	0.5400	1.4800
CPV (μm^3)	0.0283 ^{a}	0.0036	(0.0201–0.0364)	0.0114	0.0124	0.0438
CPV (%)	**0.9400** ^{b}	0.1046	(0.7034–1.1766)	0.3308	0.4900	1.4800
TPV (μm^3)	0.0569	0.0052	(0.0452–0.0686)	0.0163	0.0316	0.0772
TPV (%)	**1.8490**	0.1502	(1.5092–2.1888)	0.4750	1.3300	2.6000
Mean pore size (μm)	4.3830	0.6517	(2.9087–5.8573)	2.0610	2.2300	8.4200

[1] **Legend**: SEM—standard error of the mean, CI—confidence interval, SD—standard deviation, Min and Max—minimum and maximum values. The same superscript letters signify no statistical difference ($p > 0.05$) between the absolute values of OPV and CPV (a) and their **relative values** (**b**).

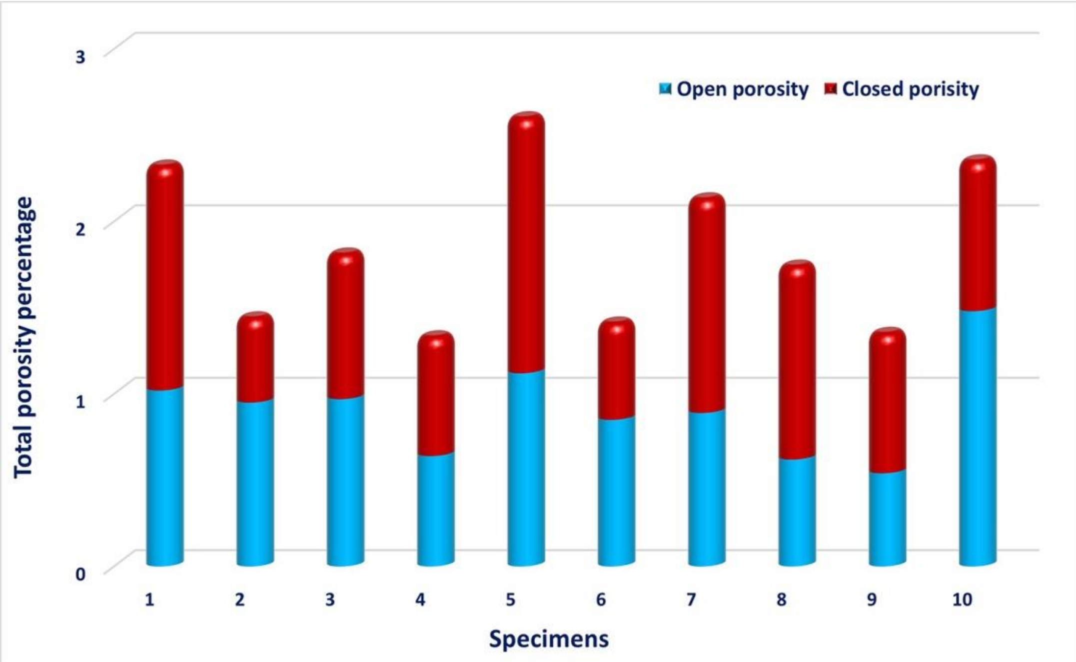

Figure 1. Distribution of TPV% (OPV% + CPV%) of Harvard MTA in the sample per specimen.

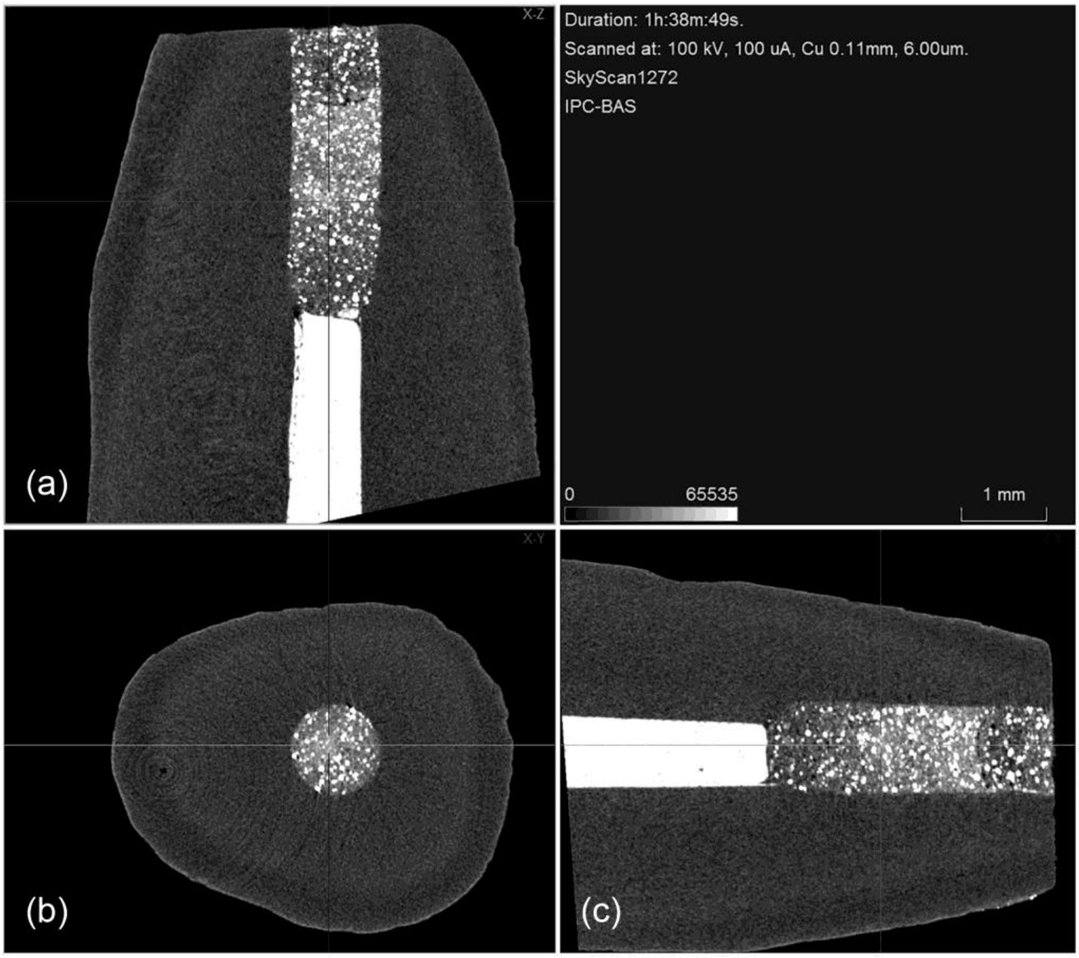

Figure 2. Representative micro-CT cross sections showing the root-end filling of Harvard MTA at 2 mm from the apex in three planes: (**a**) coronal (X–Z); (**b**) transversal (X–Y); and (**c**) sagittal (Z–Y) (scale bar = 1 mm).

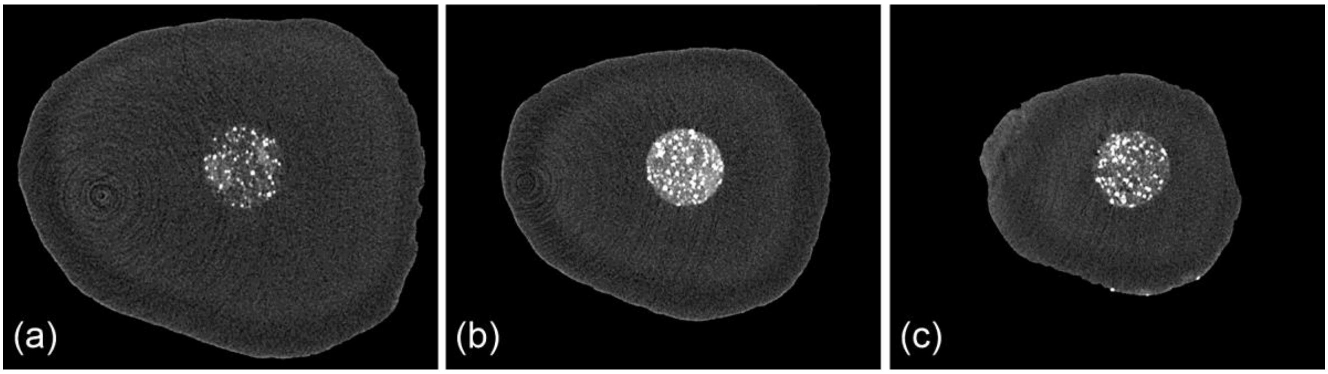

Figure 3. Micro-CT images of the filling material in transversal plane (d ≈ 1 mm) at different levels: (**a**) at 3 mm (approximately) from the resected apex; (**b**) at 2 mm; (**c**) at 1 mm.

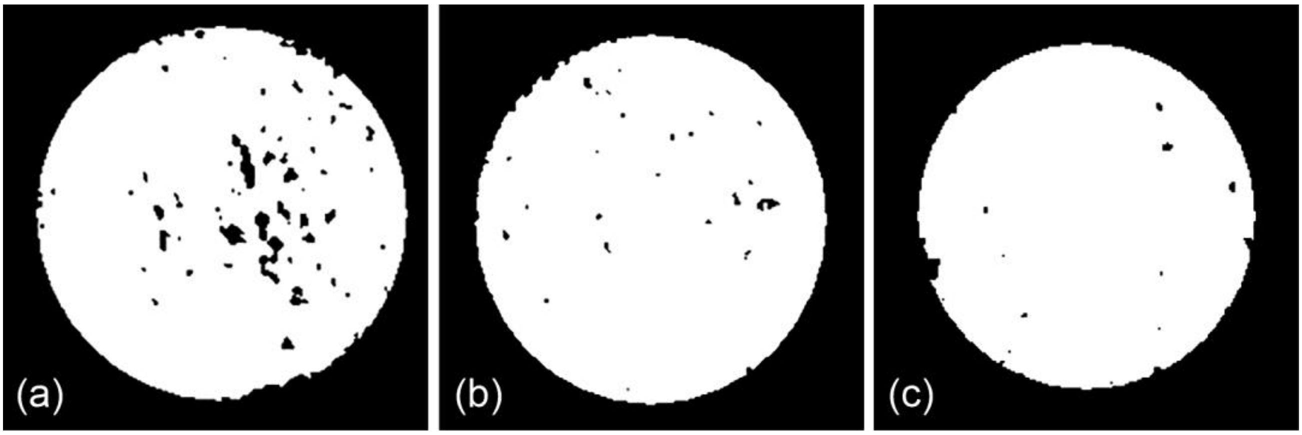

Figure 4. (**a**–**c**) Binary images of material transversal cross sections at the same levels as above (d ≈ 1 mm), displaying the porosity distribution in the VOI (pores black, material white) and highlighting the voids between radicular dentin and Harvard MTA.

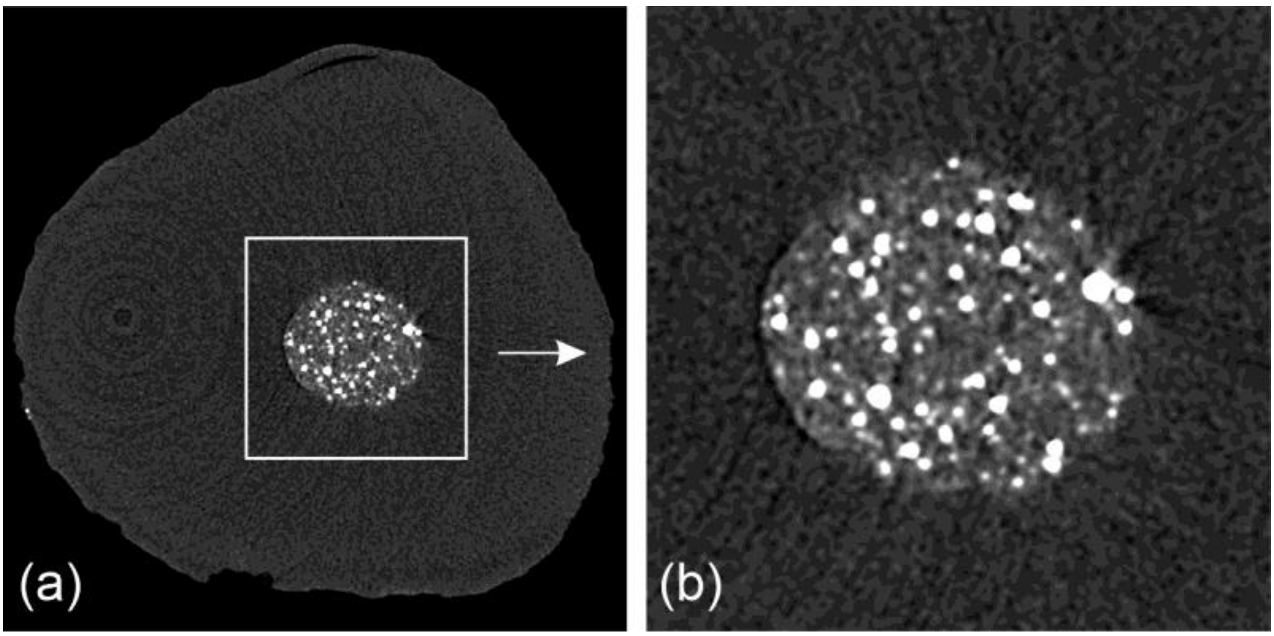

Figure 5. (**a**,**b**) Interfacial gap observed in one of the specimens' transversal cross sections.

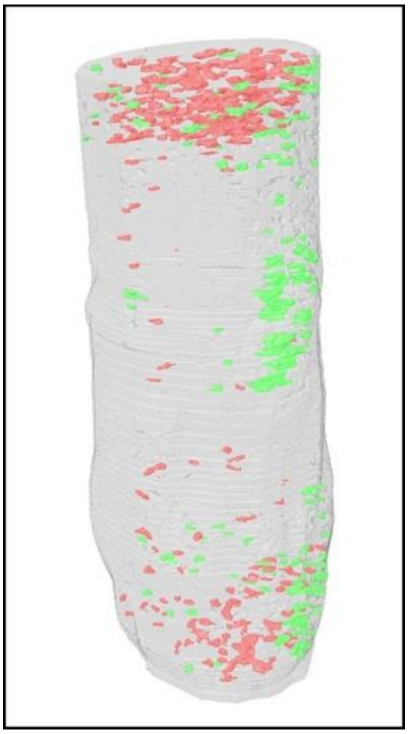

Figure 6. Representative 3D reconstruction of the porosity distribution in VOI (open pores are in green, closed pores are red; retrocavity dimensions: h ≈ 3 mm and d ≈ 1 mm). The pore size in this picture is symbolic.

The following results represent the mean absolute and relative values of the porosity characteristics found with Harvard MTA when applied as root-end filling material:

- **OPV** (or interfacial gaps and pores volume) was measured at 0.0268 ± 0.0087 mm^3, which represented 0.91% as a relative value;
- **CPV** (or internal pores volume): 0.0283 ± 0.0114 mm^3 or 0.94% of the mean retrofilling volume;
- **TPV**, or cumulative volume of gaps and voids in the tested cement, was calculated at 0.0569 ± 0.0163 mm^3 or 1.85% of the mean retrocavity volume;
- The average **pore size** (as diameter) was 4.383 ± 2.061 µm.

The pair-wise comparisons between both estimated porosity aspects **showed no significant difference** between the following pairs: *OPV* vs. *CPV* ($p > 0.05$) and *OPV%* vs. *CPV%* ($p > 0.05$). More specifically, the paired sample t-test findings for both pairs were as follows:

OPV vs. CPV (**a**): $t = -0.413$, $df = 9$, $p = 0.689$;
OPV% vs. CPV% (**b**): $t = -0.263$, $df = 9$, $p = 0.798$.

Furthermore, the descriptive statistics for the measured parameters revealed low standard deviations and somewhat narrow confidence intervals, indicating that the data are slightly dispersed relative to the mean values. The minimum and maximum values of OPV vs. CPV in volumetric units (mm^3) and as percentages are also very close: Min in absolute values (mm^3) were 0.0152 mm^3 vs. 0.0124 mm^3, and 0.54% vs. 0.49% in relative values, respectively; likewise, Max were 0.0448 mm^3 vs. 0.0438 mm^3, respectively; and maximum relative values for both parameters were found to be identical (1.48%).

The results obtained indicate that when applied for retrograde filling, Harvard MTA Universal demonstrates excellent marginal adaptability and minimum internal porosity. This novel calcium silicate cement really possesses a 98.15% filling capacity; the overall porosity of 1.85% and the small pore size observed with Harvard MTA shed light on this. Regardless of the limited sample size, it is reasonable to assume that these results are valuable based on the statistical analyses mentioned above.

4. Discussion

Most likely, there are currently about fifty different kinds of calcium silicate-based cement on the market. Based on variations in their chemistry, a system of categorization for this group of materials has been suggested [14]. All the generations of CSCs are summarized in Table 2, along with their representatives.

Table 2. Classification of calcium silicate-based cements.

Generations	Main Characteristics	Representatives
1st Generation	MTA Original	ProRoot MTA
2nd Generation	Modifications to MTA	MTA Angelus (gray and white form)
3rd Generation	Bioceramics group (New formulations)	Bioaggregate, Biodentine, Ortho MTA, MTA BIO, EndoSequence BC (iRootSP), Aureoseal, Bio MTA+, MTA Repair HP, Neo MTA Plus, Bio-C Repair, BiOfactor MTA, MTA Bio-C Pulpo, MTA Bio Rep, Endo-Eze MTA Flow, RootDent, Harvard MTA, CEM cement, ALBO-MPCA, Trioxident, One-Fill PT, etc.
4th Generation	Hybrid cements (Light-cured)	TheraCal LC

The survival rates following endodontic surgery range from 48% to 93% [15]. The prognosis and long-term success of this complex procedure depend on many factors, such as case selection, instrumentation technique, suitable equipment, the clinician's qualification, skill, and experience, the age of the patients, etc. Among them, the choice of the appropriate retrograde filling material plays a critical role [16,17].

One of the most important requirements for the root-end filling material is the ability to ensure a hermetic seal of the apical area. Inadequate sealing of the retrograde cavity is considered the main reason for the failure of endodontic surgery [17–19]. Good marginal adaptation to dentin and internal porosity of calcium silicate cements are related to their sealing capacity and ability to resist bacteria penetration and prevent the percolation of tissue fluids [20,21]. Therefore, the porosity characteristics of bioceramic materials are important determinants of healing outcomes of endodontic surgery [2,22,23].

The present study assessed quantitatively all aspects of the porosity (interfacial, internal, and total) of a new MTA brand, namely Harvard MTA Universal, used as root-end filling material. Only a single piece of research was found, evaluating the marginal adaptation of this cement at the same application site through scanning electron microscopy (SEM). El-Sherief et al. [24] reported higher average gap size values with Harvard MTA (7.44 µm) at the interface than those observed in the MTA Flow group (3.95 µm). However, the presented statistical results were inconclusive regarding the significance of this difference. To the best of the authors' knowledge, this is the first experimental micro-CT study evaluating volumetrically the marginal adaptation and internal porosity of this innovative endodontic cement.

Due to the lack of scientific evidence on **Harvard MTA**, the data obtained from the present study were compared with **similar micro-CT investigations on retrograde application** of other calcium silicate cements. Only a limited number of previous studies have used the same methodology to quantitatively assess the volume of interfacial gaps and inner porosity of selected CSCs applied as root-end filling materials. Some of them evaluated the loss of volume and density of tested CSCs exhibited after exposure to acidic or alkaline conditions, blood, or after retrieval of various intracanal medicaments, along with their marginal adaptation [25–28]. Given the differences in the study designs, our results were compared only with those obtained in similar experimental conditions, i.e., after material immersion in distilled water or in normal saline only.

In general, **Biodentine**, probably the most tested CS cement, is suggested to be superior to ProRoot MTA and other new bioceramic materials in terms of interfacial gap volume, internal porosity, and total porosity volume percentage [25,27–32]. Only Jardine et al. [27] reported a higher rate of porosity with Biodentine than MTA-Angelus. According to micro-CT investigations, Biodentine demonstrated a TPV% within a range of 2.48–6.66% and external porosity volume percentage (EPV) between 0.616–3.78%, and CPV% varied between 0.024–4.46% [23–28]. Only Toia et al. [32] reported an unusually high porosity percentage of 50.45%, making this result difficult to interpret.

While previous research indicated that Biodentine demonstrated appropriate adaptability, the OPV% of Harvard MTA (0.91%) in this investigation was significantly lower than that of almost all of those studies. Jardine et al. are the lone exception, reporting a lower OPV of 0.616%. Interestingly, they found a much greater value of CPV% with Biodentine (3.642%) than OPV% [27]. Concerning the CPV% found by us, its value is lower than the findings of some other authors [27,29]. In contrast with our results and all other research, Toia et al. [28] reported a minor CPV% of 0.024%.

Conventional MTA products, **ProRoot MTA** and **MTA-Angelus**, have been investigated to a relatively lesser extent. ProRoot MTA exhibited an external gap volume of 0.224 mm^3 [33], an EVV% of 1.882%, a CPV% of 0.021% [32], and a TPV% of 5.32% [28]. Toia et al. [32] found a porosity percentage of 51.94%. MTA-Angelus showed an EVV% of 0.888–2.07% [27,31], a CPV% of 3642 [27], and a TPV% of 4.079–8.93% [27,31]. According to our findings, Harvard MTA showed better marginal adaptation and a lower rate of micropores than most studies on conventional CSCs (first and second generations). Only Jardine et al. [27] reported a similar OPV% with MTA-Angelus, and Toia et al. [32] found an even lower CPV% with ProRoot MTA.

The porosity volume of **bioceramics**, i.e., third generation CSCs available on the market, used as retrofilling materials has been scarcely investigated. Among them, Neo MTA Plus showed the lowest EPV% of 0.888% [2,27], which is very similar to our results. Endosequence BC exhibited the lowest CPV% of 0.039% [32], with these results being significantly lower than ours. Bioaggregate exhibited the highest values of both porosity parameters: an EVV% of 9.42% and a CPV% of 17.62% [29], followed by MTA HP with a TPV% of 10.2% [34], and Retro MTA with an EVV% of 3.86% and a CPV% of 8.25% [29].

Harvard MTA Universal showed a very low percentage of total porosity volume (1.85%) in the present study, despite the fact that it was not comparative in nature. These findings suggest that this biomaterial does, in fact, possess a very high filling capacity of 99.15%. Furthermore, we found a small fraction of interfacial voids (0.91%), which shows excellent marginal adaptation of the cement to dentin. An almost equal volume of external and internal pores was found, both in volumetric units and percentages, which suggest that the material's handling characteristics allow dense condensation during its application.

As can be seen, the results reported by previous research are very divergent, both in terms of absolute and relative values of external gaps and void volume exhibited by the various CSCs. Moreover, differences in the retrograde cavity dimensions also seem to have an impact on the results reported by previous investigations. As a rule, the most common depth of retrograde cavities was 3 mm, but their diameter was a variable parameter, and even it was not specified by most authors. Therefore, the absolute values of the results found by other authors were not mentioned, and only relative values (in percentage) were compared and discussed. Overall, compared to other examined biomaterials, the porosity rate of Harvard MTA—both internal and interfacial—found in this work was lower than that of most of the previously cited authors.

The higher porosity of conventional MTA products, observed by other investigators, may be due to the inclusion of bismuth oxide in their composition as a radiopacifier [35]. Harvard MTA also contains bismuth oxide. It has, nevertheless, demonstrated a low porosity percentage. It was suggested that **merwinite** (calcium magnesium orthosilicate) may be responsible for its advantageous characteristics due to its excellent biological and physicochemical properties [9].

Magnesium-containing silicate ceramics and nanocomposites that have been researched for biomedical applications have recently gained serious scientific interest due to their proven bioactivity and ability to form an apatite-like layer. One of the fundamental minerals utilized for producing those types of biomaterials is merwinite [9,36,37]. It generally demonstrated low to partial solubility in a variety of test conditions [38,39]. The ceramics containing this mineral have exhibited high reactivity in SBFs. Their dissolving behavior in these media is quite intriguing, as they simulate clinical conditions [36,37].

Mihailova et al. evaluated the apatite layer produced on the surface of such ceramics using the Energy Dispersive Spectroscopy (EDS) technique. They discovered in it the presence of a large amount of Ca (15.05 at%) and P (7.43 at%), while the quantities of Si (2.92 at%) and Mg (0.91 at%) were substantially lower. In parallel, Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) was used to assess the content of SBF solutions, following the in vitro test. The results showed that Ca^{2+} ions were predominantly present and that their concentration increased gradually until day fourteen of the experiment. Their quantity significantly exceeded the Ca and Mg values, indicating a low partial solubility of these ions [37].

Of particular interest is the Mg and Si ion release profile on SBF, found in the aforementioned investigation. The concentrations of Mg^{2+} and Si^{4+} increased slightly after 7 days of soaking in SBF, but after 14 days, their amounts were reduced, as the ceramics nearly completely eliminated the Mg^{2+} ions from the solution. The authors suggested that the ceramic material released Ca and Si ions and removed P ions from SBF [37].

It was speculated that the lower solubility of merwinite may be a result of the significantly lower dissolution of magnesium ions compared to calcium ions, especially at an alkaline pH [9,36]. However, there are probably more complex causes behind this. Merwinite is composed of Mg^{2+}, Ca^{2+}, and $SiO_4{}^{4-}$ ions; its crystal structure is [MgO_6] octahedral, linked at every corner by [SiO_4] tetrahedra [40]. Overall, it exhibits greater stability than the mineral–crystal structure of certain other minerals, such as such as dicalcium silicate and bredigite [38], and probably hatrurite (which consists of Ca^{2+} ions and SiO_5 polyhedra). According to Galal et al., ProRoot MTA showed higher solubility compared to Harvard MTA [9]. Considering hatrurite is the main ingredient in the ProRoot MTA composition, one can assume that its presence is the cause of this. However, there is sufficient scientific evidence to support the low solubility of this first MTA brand, which falls within the limits of the relevant ISO standard [41,42].

Low porosity and solubility for reparative endodontic cements are desirable to ensure a long-lasting seal and avoid microleakage [29]. These two properties of CSCs may be associated since a higher amount of porosity may occur after immersion in tissue fluids or in various experimental media as a function of the material solubility [35]. This can be a possible explanation for the low porosity of Harvard MTA found by us.

The inconsistency in the results obtained from our investigation and those of other researchers should also be attributed to the different testing conditions and methodologies applied. Generally, this disparity may be due to the lack of standard assessment methods. In a research series, Torres et al. [43–45] investigated the impact of various factors on the accuracy of the quantitative measurement of the porosity volume in CSCs by micro-CT, such as voxel size, image-processing software, and the radiopacity of the material. According to the authors [45], smaller voxel sizes are preferable for evaluating both the thickness of materials and the volume of interfacial voids produced by them. Moreover, the immersion period of root-end filling materials in distilled water may affect their stability, as various CSCs demonstrated volumetric changes to different extents [43].

In a recent noteworthy study, Torres et al. [45] found that the evaluated cements demonstrated a decrease in the void percentage when a greater voxel size was used. These discrepancies occurred since the micro-CT images are limited by the dimensions of the target object. If the resolution exceeds the dimensions of micropores or very thin structures, they may not be properly visualized. In the current study, the specimens were scanned at an isotropic resolution of 6 μm, which provided greater clarity and contrast of images, thus increasing their quality and reliability. Even voids smaller than 5 μm were detected inside the VOI by the defined threshold gray levels. On the other hand, a lower spatial resolution may induce errors in the calculation of the percent volume, creating an overestimation of some parameters. Therefore, consistent protocols are needed for micro-CT research evaluating endodontic porous biomaterials [44].

Porosity is an inherent characteristic of tricalcium silicate cements. It is an important parameter for characterizing the microstructure of this group of bioactive materials that corresponds to the volume of the void space, which may contain fluid or air, over the total volume of the material. According to accessibility, the pore system can be divided into two main categories: open and closed porosity [46]. External (interfacial) pores that have a continuous channel of communication to the outer surface (so-called blind or interconnected pores) constitute an open porosity fraction. A hydroxyapatite layer is formed during the hydration process of CSCs as a result of the precipitation of calcium and hydroxyl ions. It was suggested that this layer provides chemical bonding between the material and the dentin wall [29]. In fact, a pore structure develops during the cement hydration, thus forming micropores within the material and resulting in the formation of gaps or voids in the cement-to-dentin interface [46,47].

Open (interfacial) porosity adversely affects the marginal adaptation of the root-end filling material and its sealing ability. It increases the permeability of the cement, thus allowing the tissue fluid percolation and the flow of microorganisms and their byproducts. Liquid sorption takes place as well. For this reason, the volume of the open pores is also referred to as the active or effective pore volume. It sheds light on the hermeticity of sealing, provided by the retrofilling at the interface [46,48].

Closed (internal) porosity, or residual porosity, refers to micropores having no communication with the surrounding dentin walls. It occurs as a result of the spaces between the unhydrated cement particles. After the material hydrates, water fills these empty spaces. As the hydration reaction progresses, the hydration products fill these gaps and the porosity decreases; however, if excess water is used during mixing, it gradually evaporates and leaves unfilled voids. It was considered that the volume of micropores inside MTA does not affect the marginal adaptation because it represents a small fraction [35]. Moreover, the number of the internal pores decreases as the cement ages [46].

From another perspective, the porosity may be beneficial to the hydration procedure of CSCs and increase their capacity to release bioactive ions. According to Eskandari et al. [49], a moderately negative association was found between the porosity, flexural strength, and sealing ability of the materials, which can lead to their weakening. Celikten et al. [29] found that material condensation with ultrasonic activation reduced the pore amount in two of the tested CSCs (Retro MTA and BioAggregate). However, Biodentine demonstrated similar results when utilizing different placement techniques.

Nowadays, **micro-computed tomography** (micro-CT) has been introduced and accepted as an innovative non-destructive method that can provide important data on the physicochemical properties of materials [30]. With high resolution, appropriate segmentation, and an image analysis approach, it may be used to quantitatively assess the interfacial gaps and filling capacity of CSCs with higher accuracy, thus overcoming some shortcomings of the SEM method [44,50]. This new technology may be used to correlate volumetric changes with resolution and dimensional variations in endodontic materials [29,50]. Furthermore, it allows the same specimen to be used at different time intervals of analysis, with a high level of detail [30].

Limitations and future research: It is acknowledged that this experimental study is a pilot and that the sample is limited. It has some other potential limitations as well. First, the volume of the retrocavities prepared was not exactly similar; however, the difference between the specimens was insignificant. It should be noted that in the larger cavity, it was easier to insert and condense the material. Second, due to artifacts resulting from the strongly absorbing particles inside the cement, some artifacts mimic voids. Thus, the volume fractions may be slightly overestimated. Moreover, the study design did not involve the use of simulated tissue fluid or other immersion media.

Meanwhile, new modifications of this restorative MTA brand were proposed, apart from the MTA Universal, such as **Harvard MTA-Retro** (precisely designed for retrograde application), Harvard MTA-CAP, Harvard MTA-PT, Harvard MTA-Repair, Harvard MTA-Ortho, and Harvard MTA-RootSeal, particularly suitable for specific endodontic purposes (i.e., pulp capping, pulpotomy, filling of root perforations and root canals) [51]. Further research on the impact of different environmental conditions on the properties of this novel bioactive cement is needed, including its new variants, in order to mimic more closely the clinical scenario and gain clinically relevant results. Since the available scientific evidence is still controversial, more research is required to compare the Harvard MTA with other CSCs in order to select the most effective root-end filling material for clinical practice.

5. Conclusions

In conclusion, Harvard MTA Universal showed excellent marginal adaptation and filling capacity in terms of interfacial and internal porosity. Our findings suggest that this new MTA brand has superior physicochemical properties from the perspective of clinical application and may be considered an efficient alternative to conventional MTA products. Further comparative research on the sealing ability of this biomaterial is needed to verify the results obtained in the present study.

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