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Micro–CT evaluation of MTA compaction techniques in 3D-printed teeth with simulated perforating internal root resorption: an in vitro study

Öznur Sarıyılmaz[1], Evren Sarıyılmaz[1*], Gülşah Uslu[2], Cangül Keskin[3] and Ali Keleş[4]

Abstract

Background This study aimed to compare the effectiveness of manual compaction, indirect ultrasonic activation, and a novel sonic-activated endomotor in reducing voids during MTA placement in perforated internal root resorption cavities (IRR).

Methods Thirty standardized 3D-printed resin teeth with simulated perforating IRR cavities (4 mm in diameter, located 4 mm from the apex, with a 2 mm buccal perforation) were fabricated. The samples were randomly divided into 3 groups: *Manual compaction*: MTA was placed and compacted using hand pluggers. *Ultrasonic activation*: MTA was placed and indirectly activated with an ultrasonic device at 30% power for 3 cycles of 10 s each. *Sonic-activated endomotor*: MTA was placed and compacted using the 812 MT endomotor. Specimens were stored at 37 °C in 100% humidity for 1-week. Micro-computed tomography (micro-CT) was used to evaluate the void volume. Intergroup comparisons were conducted using the Kruskal–Wallis test at a 5% significance level.

Results The mean void volumes were 6.49 mm^3 in the manual compaction group, 2.61 mm^3 in the ultrasonic activation group, and 3.89 mm^3 in sonic-activated endomotor group. Although the manual compaction group exhibited the highest void volume, the differences among the groups were not statistically significant ($P > 0.05$).

Conclusions Within the limitations of this in vitro study, all three MTA compaction techniques demonstrated comparable outcomes in the compaction of MTA in perforating IRR cavities. These findings suggest that, in such cases, the choice of technique may be guided by operator preference and clinical circumstances rather than expected differences in void reduction.

Keywords Internal root resorption, MTA, Ultrasonic activation, Sonic-activated endomotor, 812 MT

*Correspondence:
Evren Sarıyılmaz
evrensariyilmaz@yahoo.com; evren.sariyilmaz@comu.edu.tr
[1]Department of Endodontics, Faculty of Dentistry, Çanakkale Onsekiz Mart University, Çanakkale, Türkiye
[2]Private practice, Idadent Oral and Dental Health Clinic, Çanakkale, Türkiye
[3]Department of Endodontics, Faculty of Dentistry, Ondokuz Mayıs University, Samsun, Türkiye
[4]Department of Endodontics, Faculty of Dentistry, Bolu Abant İzzet Baysal University, Bolu, Türkiye

Introduction

Internal root resorption (IRR) is a chronic inflammatory condition characterized by the progressive destruction of dentin by clastic cells, typically triggered by pulpal inflammation due to trauma or infection. Managing IRR cases poses clinical challenges due to the presence of irregular and inaccessible cavities that are inherently formed within the root canal system as a result of the resorptive process [1]. Achieving complete and homogeneous obturation of these defects is crucial for sealing the lesion and preventing reinfection.

Thermoplasticized gutta-percha techniques have been shown to improve the adaptation of fillings to the irregular internal anatomy of resorptive cavities [2–4]. However, in cases of perforating internal resorption (IR), where communication with the periodontal tissues exists, the use of warm gutta-percha techniques may be contraindicated. In such cases, bioactive hydraulic silicate cements such as mineral trioxide aggregate (MTA) or Biodentine are widely preferred due to their sealing ability and biocompatibility [1, 5–7].

One of the main limitations of MTA is the technical difficulty in delivering and compacting it into irregular cavities, particularly in perforated defects [8]. Despite the widespread use of MTA in such situations, there is no consensus on the optimal technique for its placement. Some studies suggest that ultrasonic activation may improve filling density and adaptation, whereas others report comparable or less favorable outcomes compared with manual compaction, indicating that current evidence is inconclusive and further research is needed to clarify its effectiveness [9–15]. Ultrasonic activation has been reported to reduce bacterial leakage [16] and enhance the bond strength of MTA [15].

Recently, a novel sonic-activated endomotor (812 MT, Guilin Woodpecker Medical Instrument Co., Guilin, China) has been introduced. According to the manufacturer, this device combines sonic vibration with rotary movement to enhance the delivery and compaction of MTA into anatomically complex regions, such as lateral canals and resorption defects [17]. Given its combined sonic and rotary motion, the 812 MT may facilitate the placement and adaptation of MTA in anatomically complex regions such as lateral canals and resorption cavities, potentially improving sealing ability and clinical outcomes. However, to date, no study has evaluated the effectiveness of this device in compacting MTA, and its performance remains unverified. Therefore, the present study aimed to compare the compaction quality of MTA placed using 3 techniques, manual compaction, indirect ultrasonic activation, and a sonic-activated endomotor, in standardized 3D-printed teeth with simulated perforating IR cavities. Given its high spatial resolution and ability to provide non-destructive, three-dimensional (3D) analysis, micro-computed tomography (micro-CT) was employed to accurately quantify and compare the volume and distribution of voids resulting from each technique. The null hypothesis was that there would be no significant difference in the void volume or percentage among the three MTA compaction techniques.

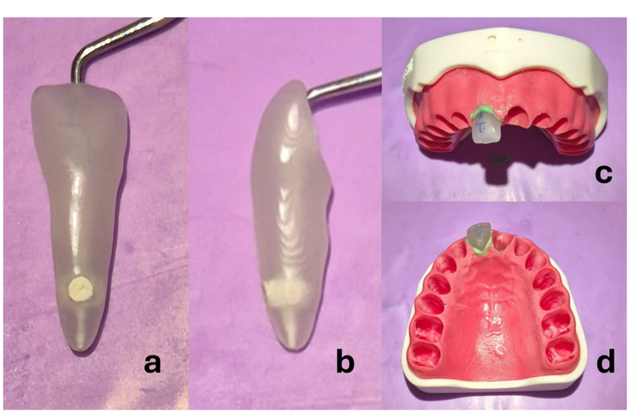

Fig. 1 (**a**) Buccal view of the tooth, (**b**) Mesial view of the tooth (**c**, **d**) Image of the tooth placed in the endodontic training model

Materials and methods

The required sample size was determined using G*Power 3.1 software (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany), based on the effect size data from a previous study (0.691) [18]. The analysis employed an F-test statistical family with an alpha level of 0.05 and a statistical power of 0.90. The analysis indicated that the minimum sample size of 10 per group was required to detect significant differences among groups.

A total of 30 radiopaque resin teeth with standardized perforating IR cavities were fabricated. The resorption defects were located 4 mm from the apex, with a consistent diameter of 4 mm. A 2-mm-diameter perforation was designed on the buccal wall of each cavity. The simulated root canals had an apical canal diameter of size 50.04 with no further instrumentation required. To replicate clinical conditions, the teeth were placed in the sockets of an endodontic training model, with the periodontal ligament simulated using a layer of light-body silicone impression material (Fig. 1).

In all specimens, the root canal segment apical to the IR cavity was filled using manual compaction of MTA (ProRoot MTA, Dentsply, Tulsa, OK, USA). A size 0 (yellow) MAP system tip (Produits Dentaires SA, Vevey, Switzerland) was used to deliver the material 2 mm short of the working length, and compaction was performed up to the coronal boundary of the resorption cavity using a Machtou Hand Plugger sizes 1/2 (VDW, Munich, Germany). The quality and extension of the apical MTA fill were verified using periapical radiographs taken from both buccolingual and mesiodistal projections to ensure adequate compaction and proper positioning prior to proceeding with the experimental procedures. Following this standardized apical filling procedure, the samples were randomly assigned to one of the 3 groups using a computer-generated random number table, based on the technique used to compact MTA within the cavity.

Manual compaction group: MTA was prepared according to the manufacturer's instructions and delivered into the resorption cavity using a size 1 (red) MAP System carrier. Compaction was performed with a hand plugger sized 3/4 (VDW). The root canal was filled with MTA to 3 mm above the coronal margin of the resorption defect as assessed under direct vision using a marked periodontal probe for reference.

Ultrasonic activated compaction group: MTA was delivered into the resorption cavity using a size 1 (red) MAP System carrier and condensed with a hand pluggers sized 3/4 (VDW). Following compaction, the plugger was left in the canal, and ultrasonic energy was indirectly applied by contacting the ultrasonic tip (ETBD, Acteon Group, France) to the plugger for 10 s. Ultrasonic activation was performed using the VDW Ultra device (VDW) at 30% power settings. Ultrasonic activation was repeated 3 times during the filling of the resorption cavity. The root canal was filled with MTA up to 3 mm above the resorptive defect as assessed under direct vision using a marked periodontal probe for reference.

Sonic-activated endomotor (812 MT) group: MTA was delivered into the root canal using a size 1 (red) MAP System carrier, then a ProTaper Gold F2 file (Dentsply Maillefer, Ballaigues, Switzerland) was attached to the 812 MT device and operated in T-mode + according to the manufacturer's instructions. In this mode, the file was inserted into the IR cavity up to the apical boundary of the defect at 90° SGP and 150 rpm. Then, MTA was compacted using a counter-clockwise (CCW) up-and-down motion at 100 rpm with sonic activation for 10 s. The device was switched to clockwise (CW) rotation with sonic activation and then returned to CCW to continue compaction.

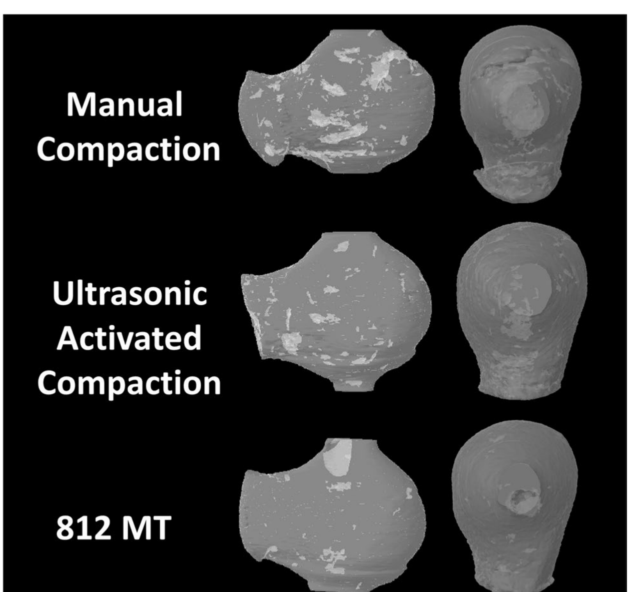

Fig. 2 Representative 3D reconstruction of one specimen from each group

After MTA was activated and compacted using the device, compaction was further supported by a hand pluggers size 3/4. The cavity was filled to 3 mm above the IR area as assessed under direct vision using a periodontal probe marked for reference.

A moist cotton pellet was placed over the MTA in all samples to facilitate setting, and the access cavities were temporarily sealed. After the setting reaction was completed, the cotton pellet was removed, the cavities were re-sealed with a temporary filling. All specimens were then stored in a laboratory incubator (Nüve, Ankara, Türkiye) with a moistened cotton roll placed inside to maintain 100% humidity at 37 °C for 1 week.

Resin specimens were mounted on a high-resolution micro-CT system (SkyScan 1,272; Bruker-microCT, Kontich, Belgium) operating at 90 kV and 111 µA with a 1 mm Al filter. Prior to each scan, the detector underwent air calibration. For each sample, slices with a pixel size of 9 µm were obtained using a camera with a pixel size of 7.4 µm. The scanning process was performed with a 1.800 ms camera exposure time, 2 × 2 binning mode, and a 0.5° rotation step in 360° rotations around the vertical axis. Reconstruction of the data was carried out using Nrecon software (v. 1.6.7.2, Bruker-microCT), with smoothing set to 2 and 40% beam hardening applied. The reconstructed images were transferred to CTAn software (v. 1.13, Bruker-microCT) for void volume analysis. The MTA void volume within the internal resorption cavity was measured for each sample. Representative 3D images of MTA fillings were produced using CTVol (2.3.2.0, software Bruker-microCT) (Fig. 2).

Statistical analysis

Since the Shapiro-Wilk test indicated that the data deviated from normal distribution ($P < 0.05$), intergroup comparisons of void volume (mm^3) and void percentage (%) were performed using the Kruskal-Wallis test, with the level of significance set at 5% in SPSS Version 26.0 (IBM Corp., Armonk, NY, USA).

Results

The mean void volumes were 6.49 mm^3 in the manual compaction group, 2.61 mm^3 in the ultrasonic activation group, and 3.89 mm^3 in the 812 MT group (Table 1). Although numerical differences were observed among

Table 1 Means ± standard deviations of void volumes and void percentages in groups

Groups	Void volume (mm^3)	Void percentage (%)
Manual Compaction	6.49 ± 5.78[a]	21.63 ± 18.29[a]
Ultrasonic Activated Compaction	2.61 ± 1.13[a]	8.70 ± 3.56[a]
812 MT	3.89 ± 2.67[a]	12.96 ± 8.44[a]

Different superscript letters indicate statistically significant difference among filling groups ($p < 0.05$)

the groups, statistical analysis revealed no significant difference in void volume and percentage ($P > 0.05$).

Discussion

The present study evaluated the compaction quality of MTA using 3 different techniques (manual compaction, indirect ultrasonic activation, and 812 MT) in simulated perforating IR cavities. Although the lowest mean void volume was observed in the ultrasonic activation group, followed by the 812 MT, the differences among the groups were not statistically significant. Therefore, the null hypothesis was accepted.

In vitro studies [3, 19, 20] evaluating the quality of fillings in teeth with IR have often used artificial cavities created by burs or acids. While these techniques provide valuable insights, they face limitations in replicating irregular cavity designs that closely resemble clinical situations as well as in standardizing cavities across samples. To overcome these challenges, resin-based models with standardized IR cavities have been introduced [4, 18]. The use of standardized 3D-printed resin teeth has allowed for high reproducibility and uniform defect dimensions across samples, overcoming a common limitation in endodontic simulation studies. Therefore, in our study, radiopaque resin 3D-printed teeth with standardized IR cavities and perforation sizes were used.

In previous studies, the effectiveness of filling IR cavities has been evaluated using radiographic imaging [21], image analysis software on sectioned tooth models [2, 22], cone-beam computed tomography [20], or micro-CT [3, 4, 18]. While radiographs and image analysis software provide only two-dimensional (2D) measurements, and CBCT's lower spatial resolution can lead to the underestimation of small voids and defects [23], the present study exclusively employed micro-CT to allow for precise 3D quantification of filling quality. The application of micro-CT provided high-resolution, 3D data that surpasses the limitations of 2D imaging in detecting and quantifying voids. An evaluation based on 2D radiographic imaging and microscopy may detect only relatively larger and surface-level voids [12], micro-CT allowed for a more precise 3D assessment of void volumes.

In the present study, the compaction performance of indirect ultrasonic activation and a newly introduced 812 MT, which facilitates MTA placement through alternating clockwise and counterclockwise motions, was compared with conventional manual compaction. According to the manufacturer, the 812 MT is effective in delivering MTA into narrow anatomical areas such as lateral canals and can be employed during MTA obturation of the root canals. No statistically significant differences were observed among the techniques; however, void volumes varied numerically between groups. This finding partially diverges the results of a previous study reporting that hand compaction resulted in superior adaptation to the canal walls and fewer voids compared to direct ultrasonic activation [12]. However, several methodological differences may account for this discrepancy, such as direct application of ultrasonic energy without supplemental compaction with a plugger and the use of 2D evaluation.

The irregular and inaccessible geometry of IRR cavities presents a considerable challenge for obturation, particularly when using materials like MTA that are sensitive to handling and compaction. Numerous studies have investigated the impact of ultrasonic activation on the sealing ability, physical properties, porosity, and adaptation of hydraulic calcium silicate fillings [8–13, 15, 24], and the effect of ultrasonic activation on MTA compaction, especially when used as an apical plug [14], for managing internal resorption defects [11], and in root canals with varying morphologies employing micro-CT analysis [9, 10]. Consistent with our results, these studies also reported no significant difference between manual compaction and ultrasonic activation [10, 11, 14]. In this study, the use of ultrasonic or sonic energy did not provide superiority over MTA compaction with a plugger. This may be attributed to several factors. First, the transmission of sonic or ultrasonic energy within the MTA may differ. As the ultrasonic energy pushes the MTA into the root canal wall, the ultrasonic tip may leave a void in the material content as it moves away from the canal [12].

A previous in vitro study [8] investigated the effect of indirect ultrasonic activation applied for 1, 5, and 10 s during MTA compaction and compared with manual compaction in terms of void volume. The authors reported that increasing the duration of activation reduced the number of voids; however, manual compaction still resulted the lowest overall void formation. In the present study, ultrasonic activation was applied for 3 cycles of 10 s, which was identified as the most effective activation duration in the literature [8]. While El Mathia et al. [8] concluded that manual compaction was superior, our results demonstrated comparable outcomes across all groups. This difference may be attributed to variations in natural root canal morphology and the configuration of the IR cavities, which can influence the distribution and effectiveness of ultrasonic energy during MTA placement.

The combination of 1-sec indirect ultrasonic activation with manual compaction has been reported to result in significantly denser fills compared to manual compaction alone [13]. In that study, fill density was assessed by weighing the specimens after compaction. While weight-based methods provide an estimate of bulk material density, they may be affected by factors such as residual moisture content and may not detect internal micro-voids. In contrast, the present study utilized micro-CT, which enables detailed 3D analysis of internal voids. These differences in assessment methodology likely reflect the distinct aspects of fill quality each approach captures and underscore the value of complementary evaluation techniques in this area of research.

From a clinical perspective, void formation within MTA fillings may compromise the long-term success of treatment by providing potential pathways for microleakage and bacterial penetration [16]. Therefore, minimizing void formation is essential to ensure an optimal seal and improve the prognosis of the treated tooth. The finding that all three techniques yielded comparable void volumes suggests that, in large perforating IR cavities, the choice of MTA placement method may be guided by operator preference, instrument availability, and ease of use rather than by expected differences in void reduction. However, clinicians should consider that indirect ultrasonic activation and the 812 MT may offer potential advantages in cases with complex or narrow anatomies, where improved flow and adaptation of MTA could be more critical. The manufacturer claims that the device enables effective MTA delivery into narrow anatomical regions, such as lateral canals; however, no studies have yet validated this assertion. In the present study, MTA compaction was evaluated within a large IR cavity, where the performance of the device or ultrasonic activation may not differ significantly from that of manual compaction due to the wide and irregular nature of the defect. Future research should aim to assess the efficacy of the 812 MT device in delivering MTA into more constricted areas such as lateral canals and isthmuses.

Some limitations should be acknowledged. First, while the standardized resin models allow for experimental control, the models do not exhibit the irregular dentin surface by the resorption process and lack the histological and biomechanical properties of natural dentin. Therefore, the findings may not fully reflect the clinical performance of MTA in natural teeth. The second limitation is the pressure applied to the material during condensation, which is an uncontrollable variable [25]. Third, this study focused solely on the evaluation of void volume; parameters such as dentin adaptation and long-term sealing ability were not assessed. These aspects are critical for predicting the clinical performance of MTA fillings and should be incorporated into future research. Further studies should also investigate the correlation between void volume and sealing ability using natural teeth and in vivo models to enhance the clinical relevance of the findings.

Conclusion

This study evaluated the impact of manual compaction, ultrasonic activation, and 812 MT on void formation in MTA compaction within IR cavities using micro-CT. Within the limitations of this in vitro study, all the three MTA compaction techniques, manual, ultrasonic, and 812 MT, demonstrated statistically similar performance in simulated perforating IR cavities.

Abbreviations

IRR	Internal root resorption
MTA	Mineral trioxide aggregate
micro-CT	Micro-computed tomography
CBCT	Cone-beam computed tomography

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Authors' contributions

Conceptualization: Ö.S. and G.U.; Formal analysis: C.K.; Investigation and Methodology: Ö.S. and G.U.; Resources: E.S.; Supervision: C.K. and A.K.; Visualization: C.K., Ö.S. and E.S.; Writing – original draft: E.S.; Writing – review & editing: G.U., C. K., and A.K.

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Data availability

The data sets can be accessed on request to corresponding author.

Declarations

Ethics approval and consent to participate

Not Applicable. Ethical approval was not required for this study, as 3D-printed resin tooth models simulating perforating internal resorption cavities were used.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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