



A Comparative Volumetric Analysis of Obturation Techniques Using a Bioceramic Sealer in Simulated Internal Root Resorption

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Abstract

Introduction: Internal root resorption (IRR) creates irregular canal irregularities that complicate cleaning and obturation. This in vitro study evaluated the obturation quality of a bioactive root canal sealer (Bioactive RCS) using different filling techniques in simulated IRR cavities. **Materials and Methods:** Forty extracted mandibular premolars were prepared to size F3. Artificial IRR cavities were induced in the middle third via a sectioning method. Samples were randomized into four groups (n=10): Single Cone (SC), Bulk Fill (BF), Bulk Fill with Ultrasonic Activation (BF+UA), and Continuous Wave Compaction (CWC). Pre- and post-obturation Cone-Beam Computed Tomography (CBCT) scans were analyzed using 3D Slicer software to calculate the Percentage of Obturation Volume (POV). Statistical analysis was performed using one-way ANOVA and Tukey HSD tests ($P<0.05$). **Results:** No technique achieved complete 3D obturation. The CWC group demonstrated the highest total POV ($94.15\pm1.63\%$), followed by SC ($90.66\pm1.77\%$). Both CWC and SC resulted in significantly higher obturation volumes compared to BF+UA ($85.07\pm2.30\%$) and BF ($83.08\pm2.14\%$) ($P=0.001$). While CWC performed best across all root thirds, the SC technique showed stable POV consistency across coronal, middle, and apical sections. Ultrasonic activation significantly improved bulk fill performance compared to bulk fill alone, which yielded the lowest values, particularly in the apical third. **Conclusion:** Within the limitations of an in vitro hemispheric cavity model and CBCT-based volumetric analysis, CWC achieved the highest POV in teeth with simulated internal root resorption. The SC technique, combined with bioceramic sealer, produced stable/comparable POV values, representing a viable/effective alternative. Ultrasonic activation improved sealer distribution compared to passive bulk fill alone, which was the least effective method. However, POV measures immediate volumetric adaptation and does not directly confirm fluid-tight sealing; clinical correlation and assessment of long-term leakage resistance require further investigation.

Keywords: Bioceramic; Bioactive RCS; Cone-beam Computed Tomography; Internal Root Resorption; Continuous Wave Compaction Technique

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Introduction

Once the root canal space is shaped and disinfected, it must be sealed to prevent recontamination, which can compromise treatment success and lead to reinfection. The primary goal of obturation is to create a bacteria-tight/fluid-tight seal within the root canal system, preventing bacterial ingress and entombing any residual microorganisms that may remain after cleaning and shaping [1]. Due consideration must be given to preventing microleakage, both during and after root-canal

therapy, by closely monitoring the tooth's sealing. Microleakage is a significant contributor to treatment failure [2]. Obturate root canals that contain empty spaces may be susceptible to bacterial microleakage and recontamination [3]. Internal root resorption (IRR) is a pathologic process that can alter the normal root canal structure and cause complex abnormalities. IRR is linked to either root canal trauma or infection, which causes clastic activity to cause the hard tissues to be lost [4]. According to the AAE Glossary of endodontic terms, internal resorption means an inflammatory process initiated within the pulp space with loss of



dentin and possible invasion of the cementum [5]. Endodontic therapy will become more difficult because of internal resorption. Instrument passage through the coronal section of the canal, through the defect, and into the apical region is challenging when internal resorption is present. Endodontic therapy is therefore essential, involving the removal of infected pulp tissue, disinfection of the root canal system, and sealing of the root canal. However, resorptive flaws with unevenly concave properties make it difficult to properly clean and obturate them in three dimensions (3D).

The BioActive RCS is a recently created calcium-silicate-based sealer that comes premixed in a single syringe (SafeEndo Dental India Pvt Ltd, Vadodara, Gujarat, India). Utilizing "Active Biosilicate Technology," a unique mineral microaggregate chemistry that provides improved sealing, biocompatibility, and bioactivity, BioActive RCS is a bioactive bioceramic root canal sealer. Calcium silicate-based cements enhance the biomineralization process, making them an appropriate substance for successful root canal closure [6]. Because of the weakening of the remaining tooth structure, endodontic treatment results may be impacted in cases of IRR. Thus, to reinforce the tooth and enhance its long-term prognosis, a calcium silicate-based material might be required.

Kim *et al.* evaluated the quality of root canal fillings with a premixed calcium silicate endodontic sealer, applied with gutta-percha cone-mediated ultrasonic activation. They observed that ultrasonic activation significantly enhanced the distribution of the sealer along the canal walls. This technique reduced voids and improved adaptation in irregular canal spaces. The authors concluded that ultrasonically activated calcium silicate sealers may provide superior sealing ability compared to conventional single-cone methods [7]. Another study utilized CBCT to evaluate the obturation of artificial internal resorption cavities using various bioceramic techniques. They found that continuous wave compaction and single-cone with BioActive RCS provided the best filling, while Bio-C Repair with lateral compaction and bulk fill was the least effective [8]. Sariyilmaz *et al.* [9] described that when ultrasonic activation was applied with sealer, the bioceramic-based root canal sealer exhibited superior penetration efficiency into lateral canals and a better sealing ability compared to when it was not applied with ultrasonic activation. The sectioning approach has been used in numerous studies to assess obturation quality. Nevertheless, these techniques only permit a two-dimensional (2D) evaluation of filling, and some of them may cause the samples to sustain irreparable damage and lose material during the cutting process [10]. Cone-beam computed tomography is a non-destructive

technique that prevents material loss by enabling a 3D volumetric assessment of obturation quality without cutting specimens [11]. There is no research in the literature assessing the obturation quality of Bio Active RCS in filling root canals with simulated IRR and obturated with bulk fill calcium silicate-based root canal sealer using ultrasonic activation, as observed with CBCT. The aim of this in vitro study was to use CBCT to determine the percentage of obturation volume (POV) to three-dimensionally assess the efficacy of various obturation techniques and bioceramic materials in filling root canals with simulated IRR. The null hypothesis proposed that there is no difference in the total POV of the root canal between different techniques used for filling IRR and among the three levels of root canals within each technique.

Materials and Methods

For this study, forty permanent mandibular human premolars were gathered. There was no calcification, internal resorption, or previous endodontic therapy in the selected teeth, which had single canals with a completely developed apical foramen. A thin diamond disc with a thickness of 0.2 mm (Jin Guang, China) and water cooling was used to cut the coronal portion of the teeth, reducing them to 15 mm from the anatomical apex. The root canal was then inserted with a size 10 K-file (Maillefer, Dentsply, Switzerland) until the tip was visible at the apical foramen. The working length was then determined to be 0.5 mm shorter. Every specimen was inserted into a plastic container filled with heavy-body silicone impression material (Zetaplus; Zhermack, Rovigo, Italy) to facilitate handling of the samples [12]. Then, in accordance with the manufacturer's instructions, the root canals were instrumented with ProTaper Gold rotary NiTi files (Dentsply Sirona, Ballaigues, Switzerland) to a master apical file of (F3). During instrumentation, a 30-gauge side-vented needle was employed to irrigate the canals with 3 mL of 3% sodium hypochlorite [13] (NaOCl, CanalPro, Coltene/Whaledent, Altstätten, Switzerland). The roots were withdrawn from the silicon mold, and a reference mark was created on the buccal aspect of each root using a disk bur. Next, a diamond disc was used with water cooling to cut the roots horizontally 7 mm away from the root apex. Using a high-speed round (no. 6) bur (Mani Inc.) with a diameter of 2 mm, hemispheric cavities were created around the outer edge of the root canal opening in each section, with water cooling, on each half of the tooth (Fig 1). To ensure proper alignment, the root was then reinserted into the corresponding silicone mold after glue (cyanoacrylate adhesive) was carefully applied to the dentine surface surrounding the cavities to reconnect the root halves by matching the guiding mark. Cyanoacrylate adhesive has been

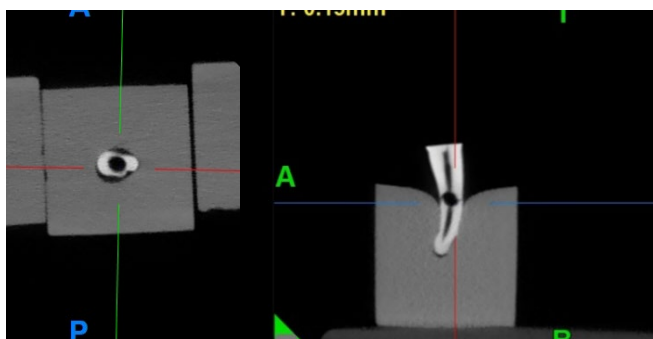


Figure 1. Artificially created IRR cavities in axial view and sagittal view

commonly used in previous in vitro endodontic studies for the reassembly of sectioned root specimens because of its ease of handling and adequate stabilization properties. During specimen preparation, no visible interference with obturation quality or interaction between the adhesive and the sealer was observed [11, 12]. To minimize the risk of adhesive disintegration, two coats of nail polish were applied to the outside of the sectioning area after the glue had set [8]. The last irrigation was done using 1 mL of 17% EDTA (Cerkamed, Poland) for 1 minute to eliminate the smear layer, and then 3 mL of 2.5% NaOCl for 1 minute [13]. This irrigation sequence was selected to first remove the inorganic smear layer with EDTA and, subsequently, allow sodium hypochlorite to dissolve residual organic debris and exert additional antimicrobial action, as recommended in contemporary irrigation protocols. To remove any remaining canal remnants, 5 ml of distilled water was used for 1 minute [8]. Paper points were then used to dry the canal, before it was put back into the silicone mold that matched. Radiographs of the teeth were taken in both buccolingual and mesiodistal directions to assess the resorption cavities [12]. The length of the sample was divided into 3 sections: coronal, middle, and apical thirds using the scissors tool in the segment editor module in Slicer 5.8.1. The prepared teeth were divided into four random groups, each with 10 samples ($n=10$), based on the techniques and materials used for obturation. Group A: Single cone (SC) technique, Group B: Bulk fill BioActive RCS (BF), Group C: Bulk fill BioActive RCS (BF) with ultrasonic activation, and Group D: continuous wave compaction (CWC) technique.

Volume Analysis of Specimens before Obturation Using CBCT

The NewTom GiANO HR 3D CEPH - CBCT Machine (Verona, Italy) was used to take radiographs of the samples before obturation, with the following settings: tube voltage of 90 kV, scan period of 15 seconds, tube current of 8 mA, and a voxel size of 75 micrometers. The total volume and the volume of each third of the root canal space were measured separately as pre-

obturation volume (X) in cubic millimeters (mm^3). The volume of the radicular space at its maximal width was determined by identifying the radiolucency in the root canal space using the segmentation tool in 3D Slicer (version 5.8.1). This tool applies density values to accurately delineate and measure root canal volumes, thereby providing comprehensive volumetric information. The 15 mm root canal model was then divided into three equal 5 mm sections (coronal, middle, and apical thirds) using the Scissors tool in the Segment Editor module, and the total volume was calculated separately for each section.

Obturation of the Root Canals

1. **The SC technique:** The working length of the master cone size F3 was assessed. Before the sealer was visible at the canal opening, the BioActive RCS was gradually inserted into the root canal, with the tip protruding past the resorption cavity. The master cone was then cut off at the orifice level after being inserted to the correct working length. To perform the coronal condensation, a manual plugger was utilized [14].
2. **The BF BioActive RCS technique:** The application tip for BioActive RCS was inserted into the canal about 3 mm less than the working length, and it was then retracted until the sealer was visible at the canal orifice [8]. No subsequent compaction or activation procedure was performed in this group. This simplified passive injection model was intentionally designed to isolate the effect of sealer placement without condensation or ultrasonic activation and to enable direct comparison with the activated and compaction-based obturation techniques.
3. **The BF BioActive RCS technique with ultrasonic activation:** The BioActive RCS application tip was introduced to a depth approximately 3 mm less than the working length and administered inside the canal, with the tip being retracted until the **sealer** became noticeable at the orifice of the canal. Ultrasonic activation was performed immediately after sealer placement, using an ultrasonic tip attached to an ultrasonic activator (Eighteenth Medical Ultra X Ultrasonic Activator, Jiangsu Province, China) in Low Output Power Mode (approx. 45 kHz and tip size #20/.02 taper). As an ultrasonic oscillates in a single plane, it was activated for 30 seconds in the mesiodistal direction and another 30 seconds in the buccolingual direction. Gentle brushing movements were performed against the root canal walls [15].
4. **The CWC technique:** After being adjusted to the working length, the F3 gutta-percha cone (Dentsply Maillefer, Ballaigues, Switzerland) was taken out and pulled back. After applying BioActive RCS to the canal's walls and cone, the cone was adjusted to the measured working length. The gutta-percha was then downpacked to 5 mm from the working length using the

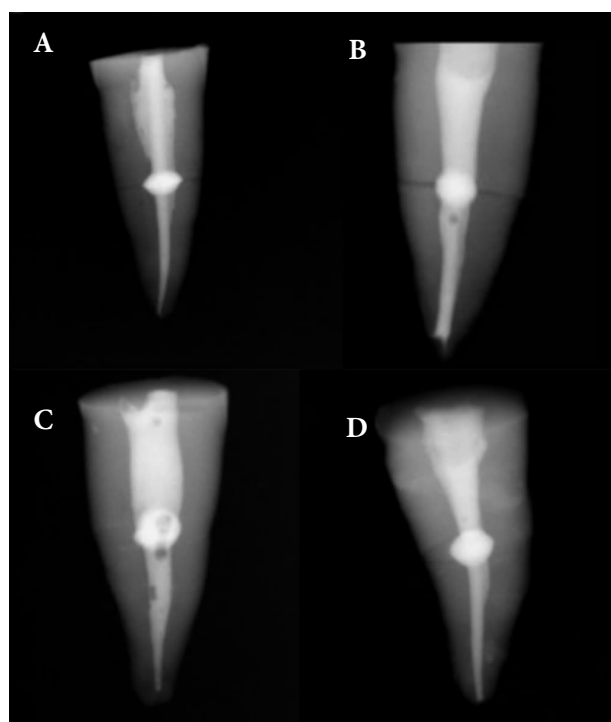


Figure 2. Obturated IRR cavities using different techniques: A) single cone technique; B) bulk fill with ultrasonic activation; C) bulk fill; D) continuous wave compaction

heat-carrier plugger (E&Q Master, MetaBiomed Co., Korea). Next, a vertical compression was applied to the heated gutta-percha. For the backfilling of the middle and coronal sections, the wireless gun was set to 180°C, and a manual plugger was used to compact the gutta-percha vertically at increments of 2 mm⁸.

Composite filling and glass ionomer cement were used to seal all channel orifices. Before the scanning procedure, the samples were kept for seven days at 37°C and 100% humidity to allow sufficient time to fully set [16]. A single operator performed the preparation, root canals, and root obturation. Fig. 2 illustrates obturated IRR cavities achieved using various techniques.

Volumetric Examination of Samples Following Obturation. Following obturation, a second CBCT scan was conducted using the same parameters to determine the post-obturation volume

(Y), which is the volume of each third and the overall volume of the filling material, in mm³. Using Slicer 5.8.1's segmentation tool, radio-opacity in the root canal was identified to calculate its maximum width. Using the following formula, the POV of each third and the total POV were calculated independently: Volume of post-obturation (Y) divided by volume of pre-obturation (X) is POV × 100 for each third of all groups and the entire root canal [8, 17].

Statistical analysis

The sample size for this study (n=10 per group) was determined using methodologies employed in similar previous investigations. To verify the statistical validity of this sample, a post hoc power analysis was conducted using G*Power (version 3.1.9.7). Based on the total percentage of obturation volume (POV) results and the observed effect size, the statistical power (1-β) was estimated to exceed 0.80. This indicates that the sample size was sufficient to detect significant differences between the obturation techniques at the 95% confidence level ($P < 0.05$).

The SPSS Statistics program, version 29, was utilized for the statistical analysis [18]. A one-way (ANOVA) test and a Tukey HSD multiple comparison test were used to statistically compare the collected data, with a P -value of less than 0.05 being considered statistically significant.

Results

Table 1 and Fig. 3 summarize the mean, standard deviation, minimum, and maximum of the POV for the total and different thirds of the root canals. The results showed significant differences in the percentage of obturation volume (POV) among techniques for the total canal and across all thirds ($P < 0.05$). Continuous wave compaction achieved the highest total POV (Mean±SD: 94.15±1.63; 91.84–96.17), followed by the single cone technique (90.66±1.77; 88.38–92.86) and bulk fill with ultrasonic activation (85.07±2.30; 81.76–89.77), whereas the bulk fill technique yielded the lowest total POV (83.08±2.14; 81.31–88.31) ($P = 0.001$) as shown in Table 1.

Table 1. Mean, Standard Deviation, and Minimum and Maximum of POV of the Different Groups of the Study

	Single Cone Technique		Bulk fill Technique		Bulk fill with Ultrasonic Activation		Continuous Wave Compaction		P-Value
	Mean (SD)	Min-Max	Mean (SD)	Min-Max	Mean (SD)	Min-Max	Mean (SD)	Min-Max	
POV Total	90.66 (1.77)	88.38-92.86	83.08 (2.14)	81.31-88.31	85.07 (2.30)	81.76-89.77	94.15 (1.63)	91.84-96.17	<0.001
POV Coronal	90.86 (3.30)	85.71-95.10	85.56 (2.25)	82.05-88.43	86.44 (2.76)	81.51-89.62	94.45 (3.31)	88.39-97.52	<0.001
POV Middle	90.34 (2.84)	85.19-95.04	83.61 (4.43)	78.40-92.86	85.03 (3.50)	81.75-91.87	93.27 (1.82)	91.20-96.69	<0.001
POV Apical	89.26 (2.56)	85.71-93.55	77.25 (2.61)	73.58-80.33	82.60 (2.38)	79.03-86.44	92.67 (2.51)	89.39-96.23	<0.001

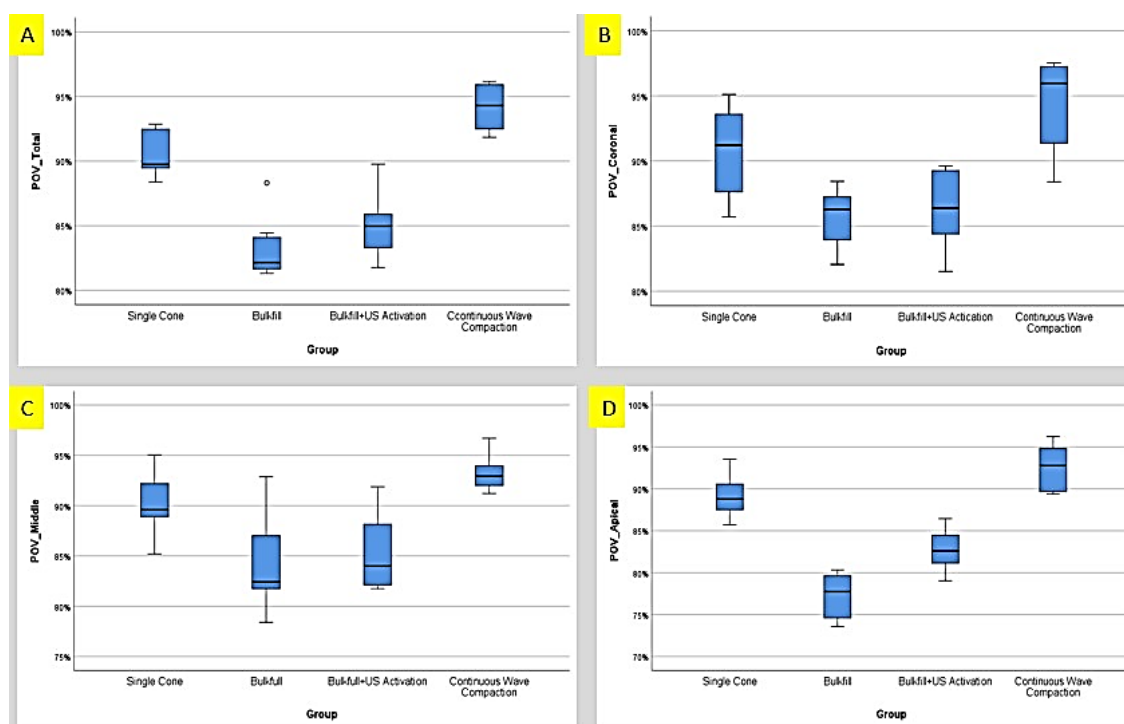


Figure 3. A) POV achieved overall; B) POV achieved in the Coronal third; C) POV achieved in the Middle third; D) POV achieved in the Apical third

At the coronal third, continuous wave compaction again presented the highest POV (94.45 ± 3.31 ; 88.39–97.52), exceeding single cone (90.86 ± 3.30 ; 85.71–95.10), bulk fill with ultrasonic activation (86.44 ± 2.76 ; 81.51–89.62), and bulk fill (85.00 ± 2.25 ; 82.05–88.43) ($P=0.001$). In the middle third, continuous wave compaction (93.27 ± 1.82 ; 91.20–96.69) and single cone (90.34 ± 2.84 ; 85.19–95.04) outperformed bulk fill with ultrasonic activation (85.03 ± 3.50 ; 81.75–91.87) and bulk fill (83.61 ± 4.43 ; 78.40–92.86) ($P=0.001$). The apical third exhibited the greatest separation among techniques, with continuous wave compaction (92.67 ± 2.51 ; 89.39–96.23) and single cone (89.26 ± 2.56 ; 85.71–93.55) producing significantly higher POV than bulk fill with ultrasonic activation (82.60 ± 2.38 ; 79.03–86.44) and bulk fill (77.25 ± 2.61 ; 73.58–80.33) ($P=0.001$).

Normality (Shapiro–Wilk) and homogeneity (Levene's) assumptions were satisfied ($P>0.05$), permitting one-way ANOVA; within-technique comparisons showed stable POV across thirds for single cone ($P=0.102$), while bulk fill produced the lowest POV apically versus coronal and middle ($P<0.001$), bulk fill with ultrasonic activation showed lower apical than middle ($P=0.011$), and continuous wave compaction demonstrated a higher apical POV than middle ($P=0.037$) (Table 2). Collectively, no technique yielded complete three-dimensional obturation; however, continuous wave compaction consistently maximized POV, whereas bulk fill without compaction produced the lowest values.

Discussion

Since some parts of the root canal walls impacted by IRR will remain unaffected by the tools, it is impossible to mechanically shape them entirely. To guarantee microbiological control, all irregularities should be obturated using root canal filling materials, even if these areas are not cleansed. Filling the resorption area with the most GP and the least amount of canal sealer is the primary objective [19]. Reinforcing teeth with IRR is essential for reducing the risk of root fracture, since these teeth may become more brittle as a result of the loss of tooth structure [18]. The introduction of bioactive calcium silicate sealers (bioceramic sealers) has marked a significant shift in the paradigm of root canal therapy. These materials not only act as a physical barrier against microbial invasion through bio-obturation, but also actively stimulate tissue regeneration [20]. According to one study, the bioceramic sealer had the strongest push-out bond with the root dentin. They discovered that it was noticeably better than sealers based on MTA and epoxy resin [21]. According to a study, utilizing bioceramic material to fill the resorption cavity and backfill strengthens the tooth more than using a gutta-percha/sealer combination for roots with internal resorption [22]. Excellent sealing with no microleakage is achieved by bioceramic sealers, which are chemically bonded to dentin and extremely biocompatible and bioactive. Additionally, they stimulate periapical healing by releasing calcium ions that have antimicrobial properties [23].

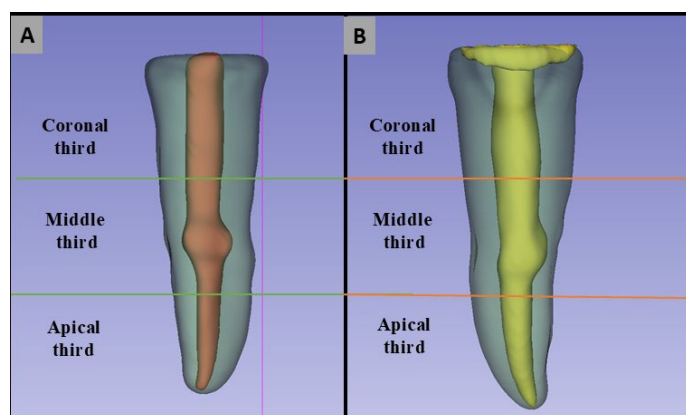


Figure 4. Three-dimensional (3D) CBCT reconstructions for calculating: A) Preobturation volume, traced red in color; B) Postobturation volume (bulk fill group C), traced yellow in color, using 3D Slicer 5.8.1

Filling adaptation, especially in apical and lateral resorption sites, remains a challenge. Bioceramic sealers have demonstrated bioactivity by stimulating healing and even regeneration of periapical tissues, supporting improved long-term outcomes. Nonetheless, prognosis is influenced by IRR location, size, and the effectiveness of microbial control and obturation [24, 25]. For these reasons, bioceramic materials were used in the current investigation.

Prior studies have used a stereomicroscope to examine IRR cavities, which can result in samples being permanently damaged and a portion of the filling material being lost during sample preparation and sectioning. However, because the tooth is only inspected at a particular cross-section, this destructive method ignores the whole root canal [26]. Because CBCT is a non-invasive technique that offers a volumetric examination, avoids material loss, and yields repeatable results, it was utilized in this study to overcome these drawbacks [27].

The first null hypothesis was rejected, as the results demonstrated that no approach resulted in full sealing of the root canals with IRR, and that the difference in POV was statistically significant. In comparison to the other groups, the bulk fill group displayed noticeably decreased total, coronal, middle, and apical POV. Fig. 4 illustrates a 3D reconstructive image of bulk fill group results in incomplete obturation in the resorptive area. This issue most likely resulted from the lack of condensation after the sealer was injected into the canal. Furthermore, air gaps might have been trapped as a result of syringe withdrawal. This conclusion is consistent with earlier studies that have shown the BF form of bioceramic sealer yields the worst outcomes [28]. These results support the findings of a previous study, which demonstrated that the single-cone technique with bioceramic sealer and the warm technique were similar in filling canals with simulated internal resorption. Even though the SC and CWC groups had comparable POV mean values, with no significant differences in the total and the three root canal thirds, the results suggest that these techniques are comparable in filling canals with simulated internal resorption [29].

These findings corroborate a prior study that showed the effectiveness of ultrasonically activated sealers in reducing void formation and raising the percentage of sealer penetration; the bulk fill with ultrasonic activation group performed better than the bulk fill without any activation or compaction group [28].

The apical third demonstrated the lowest POV in the BF group, leading to rejection of the second null hypothesis, as significant differences were observed among the coronal, middle, and apical thirds within the group. This finding may be attributed to air entrapment, lack of compaction, and the limited penetration of the delivery needle into the apical region. In contrast, the CWC group exhibited significantly higher apical POV values, possibly because the circular anatomy of the apical

Table 2. Intra-group Comparison of Mean, Standard Deviation, and Minimum and Maximum POV across Root Thirds

Group	Section	Mean (SD)	Min-Max	P-Value
Single Cone Technique	Coronal	90.86 (3.3)	85.71-95.1	<0.001
	Middle	90.34 (2.84)	85.19-95.04	
	Apical	89.26 (2.56)	85.71-93.55	
Bulk fill Technique	Coronal	85.56 (2.25)	82.05-88.43	<0.001
	Middle	83.61 (4.43)	78.4-92.86	
	Apical	77.25 (2.61)	73.58-80.33	
Bulk fill with Ultrasonic Activation	Coronal	86.44 (2.76)	81.51-89.62	<0.001
	Middle	85.03 (3.5)	81.75-91.87	
	Apical	82.6 (2.38)	79.03-86.44	
Continuous Wave Compaction	Coronal	94.45 (3.31)	88.39-97.52	<0.001
	Middle	93.27 (1.82)	91.2-96.69	
	Apical	92.67 (2.51)	89.39-96.23	

third is more compatible with thermoplasticized gutta-percha. Additionally, heat softening during the CWC technique may have produced a more homogeneous mass with improved adaptation to the canal walls. The outcome was different in the SC group, where there was no discernible variation in the quality of obturation across various root levels. This result is comparable to Liu *et al.*'s findings [29].

The single-cone technique is efficient and cost-effective, and when paired with ultrasonic activation or improved sealers, it produces minimal voids and excellent fill in simulated IRR. However, compaction techniques (continuous wave or warm vertical) typically offer the highest obturation volumes in irregular spaces. The evidence continues to highlight that neither technique guarantees complete obturation in all clinical scenarios, and hybrid/innovative methods may further improve results [8, 30, 31].

Beyond volumetric efficacy, clinical decision-making in the management of internal root resorption (IRR) must account for practical factors such as procedural complexity, cost, and the required armamentarium. The Continuous Wave Compaction (CWC) technique, while achieving the highest Percentage of Obturation Volume (POV) in this study, necessitates specialized equipment, including heat carriers and gutta-percha extruders, which increases the overall cost of treatment and requires a steeper learning curve for the clinician. Conversely, the Single Cone (SC) technique offers significant clinical simplicity and cost-effectiveness by utilizing a single master cone matched to the canal preparation size. Given that the SC technique produced stable and consistent results that were statistically comparable to CWC in this investigation, it represents a highly efficient alternative for practitioners seeking a predictable outcome without the equipment-intensive requirements of warm vertical compaction.

The high percentage of obturation volume (POV) observed in the single-cone group may be attributed to the unique physical properties of bioceramic sealers, which exhibit high flowability and a slight expansion upon setting. When the master cone is inserted, it generates hydraulic pressure that facilitates the distribution of the BioActive RCS into the irregularities of the internal root resorption (IRR) cavity. This hydraulic action, combined with the sealer's ability to chemically bond to dentin and its low film thickness, effectively compensates for the lack of active warm vertical compaction [23, 32]

Although the differences in Percentage of Obturation Volume (POV) between techniques may appear numerically modest, even a 3–5% increase in obturation quality may be clinically relevant in cases of internal root resorption, as residual voids or unfilled irregularities can serve as potential niches for

bacterial persistence and reinfection. Since none of the techniques achieved complete three-dimensional obturation, maximizing adaptation within the resorptive defect remains important to improve long-term sealing and reduce the risk of treatment failure. Nevertheless, the direct relationship between volumetric obturation and long-term clinical prognosis requires further investigation through longitudinal clinical studies.

The findings of the current study align with and expand upon previous research regarding bioceramic obturation quality. Specifically, our observation that Continuous Wave Compaction (CWC) and Single Cone (SC) techniques provide superior filling in internal root resorption (IRR) cavities corroborates the results of Sharki and Ali [8], who also reported that these techniques outperformed bulk fill methods. Furthermore, while our study demonstrated that ultrasonic activation significantly improved the performance of the bulk fill technique, particularly when compared to passive injection, this improvement was not sufficient to match the volumetric efficiency of CWC or SC. This is consistent with the findings of Kim *et al.* [7] who noted that while ultrasonic activation enhances the distribution of calcium silicate sealers along irregular canal walls, its effectiveness is still influenced by the specific obturation method and the presence of complex canal abnormalities.

Nanotechnology-modified and next-generation bioceramic sealers demonstrate promise for enhanced handling, improved antimicrobial activity, and faster setting. There are also limitations, including cost, long setting times, and the complexity of retreatment in case of failure, meaning there is an ongoing need for innovation and careful material selection [33–35].

Limitations

While the standardized sectioning method employed in this study provides a reproducible model for 3D volumetric assessment, it is a simplified representation of clinical internal root resorption (IRR). In clinical settings, resorptive defects are rarely perfectly hemispheric and often present with highly irregular, unpredictable geometries, such as coronal 'pink spot' lesions or complex 'blunderbuss' apical shapes that complicate both disinfection and 3D obturation [36]. Although this *in vitro* model allowed for rigorous comparison and accurate calculation using CBCT, it may not fully capture anatomical challenges, such as deep undercuts or narrow communications, found in naturally occurring pathologic processes. Consequently, while Continuous Wave Compaction and Single Cone techniques demonstrated high efficacy in this controlled scenario, their performance in more complex clinical defects may vary, and these results should be interpreted with caution.

It is important to note that this study relied on Percentage of Obturation Volume (POV) as the primary measure of obturation quality. While POV provides a quantitative assessment of the material's immediate three-dimensional adaptation within the resorption defect, it does not directly confirm the presence of a fluid-tight, hermetic seal. High volumetric filling serves as a prerequisite for adaptation but does not guarantee resistance to bacterial ingress or microleakage. As this study did not employ assays such as fluid filtration or dye penetration, future investigations are required to correlate these volumetric findings with the long-term sealing ability and stability of the obturation."

The current investigation was limited by the fact that it was conducted in vitro and that micro-computed tomography (micro-CT) has a higher resolution than CBCT. Even though micro-CT provides higher resolution, CBCT is widely accessible, facilitates 3D analysis with minimal specimen destruction, and improves identification, management, and prognostication of IRR, including exact delineation of lesion extent and obturation quality in all root thirds [24, 37-39]. The resolution appears sufficient for evaluating the quality of root-filling, notwithstanding certain limitations. It may be improved, though, by raising the resolution. Therefore, the use of micro-CT in future research is advised. To determine how the present findings affect the delayed results of root canal filling, further investigation is needed.

Conclusion

None of the investigated techniques achieved complete three-dimensional obturation of the simulated internal root resorption (IRR) defects. Continuous Wave Compaction (CWC) consistently produced the highest quality of obturation across all root thirds and is recommended when maximum volumetric fill is the primary clinical objective. However, the Single Cone (SC) technique with BioActive RCS proved to be a highly viable and effective alternative, demonstrating stable and consistent obturation volumes that were statistically comparable to CWC. For general practitioners, the SC technique offers a simpler, more cost-effective, and less equipment-intensive approach while maintaining high-quality management of IRR. In contrast, the passive bulk fill method without activation is the least effective approach and should be avoided, particularly in the apical third, where it yields the lowest obturation values. While ultrasonic activation significantly enhances sealer distribution compared to bulk fill alone, it does not reach the effectiveness of the CWC or SC techniques.

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Authors' contributions

Conceptualization: PR/TKS; Methodology: PR/TKS/AJJ; Formal Analysis and Investigation: PR/TKS/AJJ/IK; Writing-Original draft preparation: TKS/AJJ; Writing-review and editing: PR/TKS/AJJ/IK; Supervision: AK/FH. All authors read and approved the final manuscript.

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