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Retreatability of Bioceramic-Filled Teeth: Comparative Analysis of Single-Cone and Carrier-Based Obturation Using a Reciprocating Technique

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Abstract: Objectives: To evaluate the retreatment efficacy of premixed bioceramic sealer using a reciprocating system, comparing single-cone and carrier-based obturation techniques. Materials and Methods: Twenty-three monoradicular teeth with oval canals were divided into two groups: NeoSealer Flo with single cone (SC) and NeoSealer Flo with Guttafusion (GF). Retreatment was performed using Reciproc Blue (RB) with a crown-down technique. X-ray and CBCT images were taken to measure the remnant areas and volumes. Results: Apical patency was achieved in all the samples. The remnants were mostly distributed in the middle third in the GF group, while an equal distribution in both the middle and apical thirds was observed in the SC group. The GF group had a lower remnant area and volume after RB 50.05, respectively (0.18 ± 0.33 mm^2 vs. 0.39 ± 0.80 mm^2 and 0.36 ± 0.59 mm^3 vs. 0.51 ± 1.16 mm^3). The use of RB 50.05 led to an additional reduction in the remnant areas in the SC (14.89%) and GF (69.49%) groups, while in terms of the volume, the reductions were 20.63% and 36.36%. Conclusions: Reciprocating instruments are effective in removing remnants from root canals filled with both single-cone and carrier-based techniques. The blooming effect in CBCT imaging suggests further in vivo studies for validation.

Keywords: premixed bioceramic sealer; CaSi sealers; single-cone technique; CBCT; blooming effect

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1. Introduction

Endodontic retreatment becomes necessary when a previously treated tooth shows a persistent or recurrent infection. The success of retreatment depends on the removal of root canal materials and the eradication of bacteria that led to the treatment failure [1,2].

In recent years, there has been a significant increase in the clinical use of latest-generation premixed calcium silicate-based sealers, due to their ease of use, promising characteristics [3] and clinical advantages [4].

Traditionally limited to cold endodontic techniques, such as single-cone, these premixed bioceramic sealers are now being successfully applied in warm techniques as well, as demonstrated by recent in vivo clinical research [5–8].

Given the increased use of these sealers, there will be a higher possibility of coming across teeth that need to be retreated. The literature presents conflicting findings regarding their potential to occlude the apical foramen, compromise patency and make retreatment procedures more difficult and time consuming [9]. On the other hands, some studies assert that premixed bioceramic sealers are easier to remove compared to epoxy resin-based sealers [10,11]. Further investigations are needed to elucidate the material properties and clinical implications of premixed bioceramic sealers in endodontic therapy. NeoSealer Flo (Avalon Nusmile, Houston, TX, USA) is a premixed bioceramic-based resin-free sealer composed of tantalite (50%), tricalcium silicate (25%), calcium aluminate (25%), dicalcium silicate (10%), tricalcium aluminate (5%), and calcium sulphate (1%). Its chemical and physical properties have been described by in vitro studies, showing moderate calcium ion release, alkalizing activity and some apatite-nucleating and calcium carbonate-forming abilities after immersion in simulated body fluids [12].

Currently, only in vitro Micro-CT or Scanning Electron Microscopy (SEM) investigations have been used to assess the ability to retreat teeth filled with premixed bioceramic sealers with different techniques [13–16]. However, even if Micro-CT is considered the benchmark for assessing remnants and the three-dimensional configuration of canals, its application is restricted to laboratory research, as Micro-CT cannot be utilized in clinical in vivo settings.

The primary aim of this study is to assess whether the retreatment of premixed bioceramic sealer in oval-shaped teeth allows for the re-establishment of apical patency. The null hypothesis is that there is no significant difference in retreatment outcomes between cold and warm obturation techniques. A detailed investigation using a specialized software on digital images from periapical radiographs (phosphor plates) and cone beam computed tomography (CBCT) scans was used to evaluate this hypothesis.

2. Materials and Methods

2.1. Sample Selection and Preparation

The use of the extracted teeth for the present in vitro investigation was approved by the ethics committee (protocol no. 602-2020-OSSAUSLBO-20032).

In total, 30 single-rooted teeth with oval-shaped canals were included. Seven teeth were excluded due to the presence of canal calcifications, internal resorption or wide apex. Tooth selection was based on preoperative digital radiography. Analysis of root canal morphology was performed at 7 mm from the apex using CBCT images at axial sections. Samples with major diameter/minor diameter ratio greater or equal to 2 were included (Figure 1). Each tooth was decoronated to achieve a standardized root length of 12 ± 1 mm. The samples were individually stored in numbered containers, immersed in Hank's Balanced Salt Solution (HBSS), and placed in an incubator at 37 °C and 95% relative humidity. The samples were randomly divided into two groups based on the different obturation techniques:

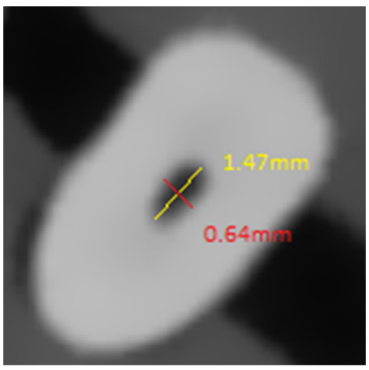


Figure 1. Axial section at 7 mm from the apex obtained from CBCT images to verify the oval shape of the canal. The length of the VL diameter is at least twice that of the MD diameter in all samples.

Group 1 (GF) = a warm obturation with Neosealer Flo and carrier-based technique.
Group 2 (SC) = a cold obturation with Neosealer Flo and single-cone technique.

2.2. Root Canal Treatment

The working length (WL) was determined by inserting a #10 K-File (Dentsply Maillefer, Ballaigues, Switzerland) into the canal until its tip was visible at the apical foramen. Gates Glidden burs (Dentsply Maillefer, Ballaigues, Switzerland) were used in the coronal third, and manual instrumentation was performed using #10, #15, and #20 K-Files until WL was reached. Canal shaping was performed using NiTi Rotate rotary instruments (VDW, Munich, Germany) 15.04, 20.04, 25.06, and a Gold Reciproc motor (VDW, GmbH, Munich, Germany). Torque and rpm settings were set following manufacturer's instructions. Canal instrumentation was performed with gentle motions with an amplitude of 2–3 mm. Dentin trapped in the instrument was removed using an endodontic sponge. A volume of 3 mL of 5% NaOCl (Niclor 5, Ogna, Muggiò, Italy) was inserted into the canal through a 5 mL syringe with a 27 G needle. This procedure was repeated until WL was reached. The treatment was considered completed when no remnants were visible on the instrument surface and the irrigant solutions appeared free of canal remnants. After mechanical instrumentation, the tooth was further irrigated with 5% NaOCl for 3 min and 10% EDTA for 1 min to achieve complete removal of the smear layer. A final irrigation with 1 mL of saline solution was performed. Instrumentation times were recorded. CBCT and X-ray images (vestibulolingual, VL, and mesiodistal, MD, projections) were taken before repositioning the samples in numbered containers and placing them in the incubator.

Group 1 (GF): Samples in group 1 (n = 11) were obturated using a carrier-based technique. The canal was dried using sterile paper points. Neosealer Flo was used in combination with Guttafusion (Guttafusion system, VDW, GmbH, Munich, Germany). The sealer was placed in the canal using a syringe positioned 2 mm from the apex. Excess sealer was removed with a paper point. The obturation material used was Guttafusion #25, which consists of a cross-linked gutta-percha core coated with gutta-percha. The carrier-based obturator was heated in the Thermaprep 2 oven for 1 min and then introduced into the canal with a slow and steady motion until reaching the WL. X-ray (VL) and CBCT were performed on the samples. The samples were reintroduced into the designated numbered containers and placed in an incubator for 30 days.

Group 2 (SC): Samples in group 2 (n = 12) were obturated using the single-cone technique. The canal was dried using sterile paper points. Neosealer Flo was placed in the canal using a syringe positioned 2 mm from the apex. The canal was filled completely until the sealer was visible at the canal orifice. Gutta-percha cone #25.06 (Dentsply Maillefer, Ballaigues, Switzerland) was slowly inserted in an apical direction until reaching the WL. X-ray (VL) and CBCT were performed on the samples. The samples were placed back into their designated numbered containers and kept in an incubator for 30 days.

2.3. Secondary Root Canal Treatment

Thirty days after the first root canal treatment, the samples were removed from the incubator to start the retreatment procedures. Retreatments involved the use of reciprocating instruments, specifically Reciproc Blue #25, #40, #50, and Gates Glidden #3–4 burs (Dentsply Maillefer, Ballaigues, Switzerland). The "crown-down" technique was used. Root canal filling material was removed in the coronal third, approximately 3–4 mm, using Gates Glidden burs. Reciproc Blue #25 file was than activated with gentle apical pressure. The instrument was gradually advanced apically with 2–3 mm amplitude and circumferential movements. Each canal was irrigated with 3 mL of 5% NaOCl and 2 mL of 10% EDTA. The retreatment procedure was considered complete when no remnants were visible on the working surface of the instrument, and the irrigant solutions appeared free of debris. After the removal of the root canal remnants, the samples were irrigated with 5% NaOCl for 3 min, 10% EDTA for 1 min, and finally rinsed with 1 mL of saline solution. This procedure was repeated for the RB25, RB40, and RB50 instruments. Radiographic assessments were performed after the retreatment with RB40 and after the retreatment with RB50.

2.4. Radiographical Analysis

Digital periapical radiographs were taken using a size 2 photostimulable phosphor plate, parallel technique, and a 30 cm focal distance. The samples and the phosphor plate were positioned on a customized model made of polyvinyl siloxane in repeatable positions for each phase of the radiographic examination sequence. The customized model was positioned on a radiolucent support, which was modified to achieve a repeatable position for housing the model. The X-ray tube was placed on a rigid plane in contact with the radiolucent support to maintain a standard distance from the customized model, on which the samples were placed (Figure S1). The DICOM files obtained were analyzed using the open-source software ImageJ (NIH software Version 1.54, Bethesda, MD, USA software version 1.54f) (Figure 2). For each sample, the region of interest (ROI) was manually delineated by a single operator. Operations to determine the ROI surface value were performed automatically by the ImageJ software. The canal area was individually measured in the coronal, middle, and apical thirds. Measurements were taken from the radiographs obtained during sample selection, after initial instrumentation, after retreatment with RB40, and after retreatment with RB50. The area of remnants was obtained using the same technique as for the canal area. The area of remnants was measured separately in the coronal, middle, and apical thirds after retreatment with RB40 and after retreatment with RB50.

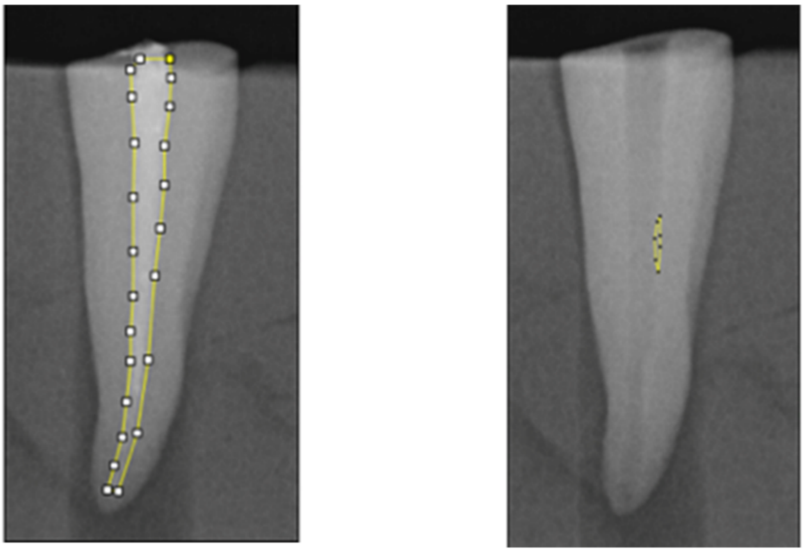


Figure 2. Methodology for quantitative analysis of the canal area and residual canal area using ImageJ software on periapical radiographs. A periapical X-ray was taken at the end of the canal obturation. On the digital image obtained, the canal area and the obturation material area were calculated by manually delineating the boundaries of the region of interest. Periapical X-ray image taken at the end of the retreatment. Residual materials are manually highlighted. The obtained image was used to calculate the canal area and the residual area, divided by root thirds.

CBCT examinations were performed following the digital radiographic procedures. The obtained DICOM files were analyzed using the open-source software Slicer 3D (Figures 3–7). The volume of the entire canal and the volume of canal filling residues were measured. The canal volume and the volume of filling material residues were manually segmented using the "segment editor" function. Manual segmentation was performed on the axial, coronal, and sagittal planes (Figure 8). Operations to determine volume measurements were automatically performed by the software using the "segment statistic" function. Measurements were taken at the preoperative level, after initial instrumentation, after canal filling, after retreatment with RB40, and after retreatment with RB50. For the CBCT images, the customized model was again positioned on the modified radiolucent support to ensure a repeatable setup. The same standardized procedure for positioning and distance maintenance was followed (Figure S1).

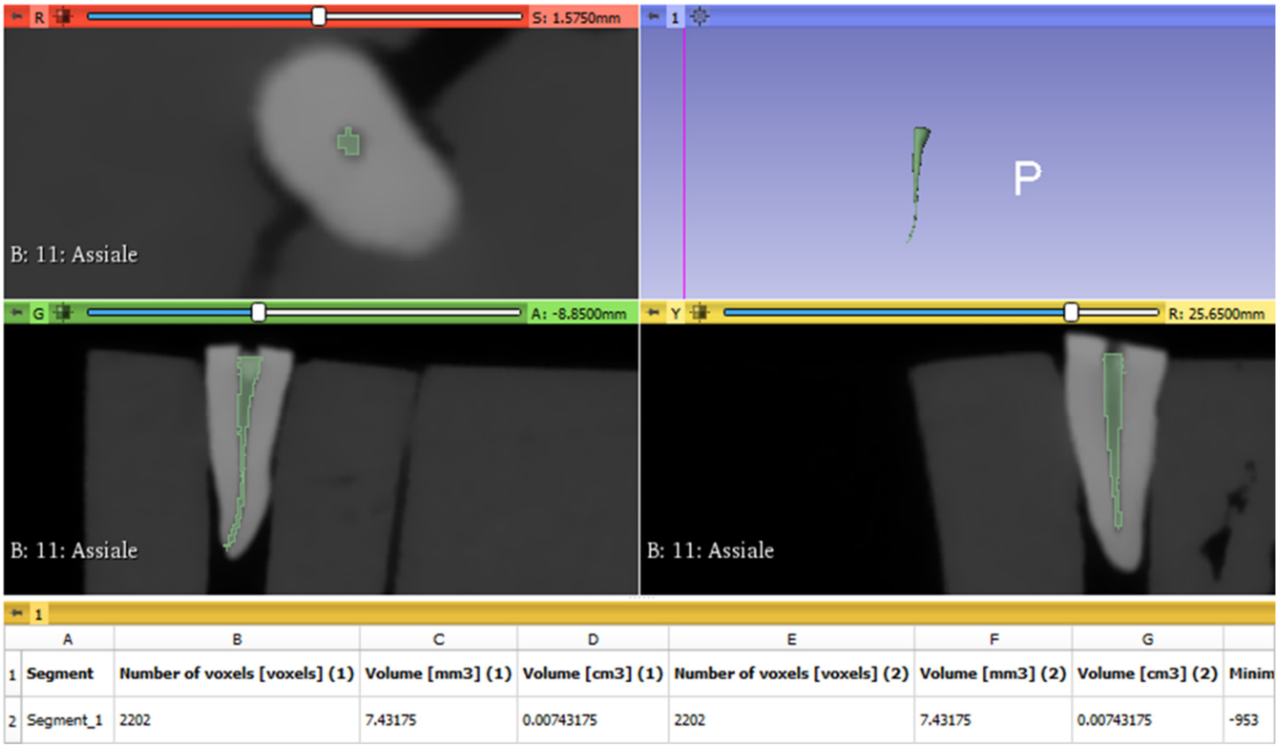


Figure 3. Methodology for quantitative analysis of the canal volume and residual canal volume using Slicer 3D software on CBCT images: preoperative.

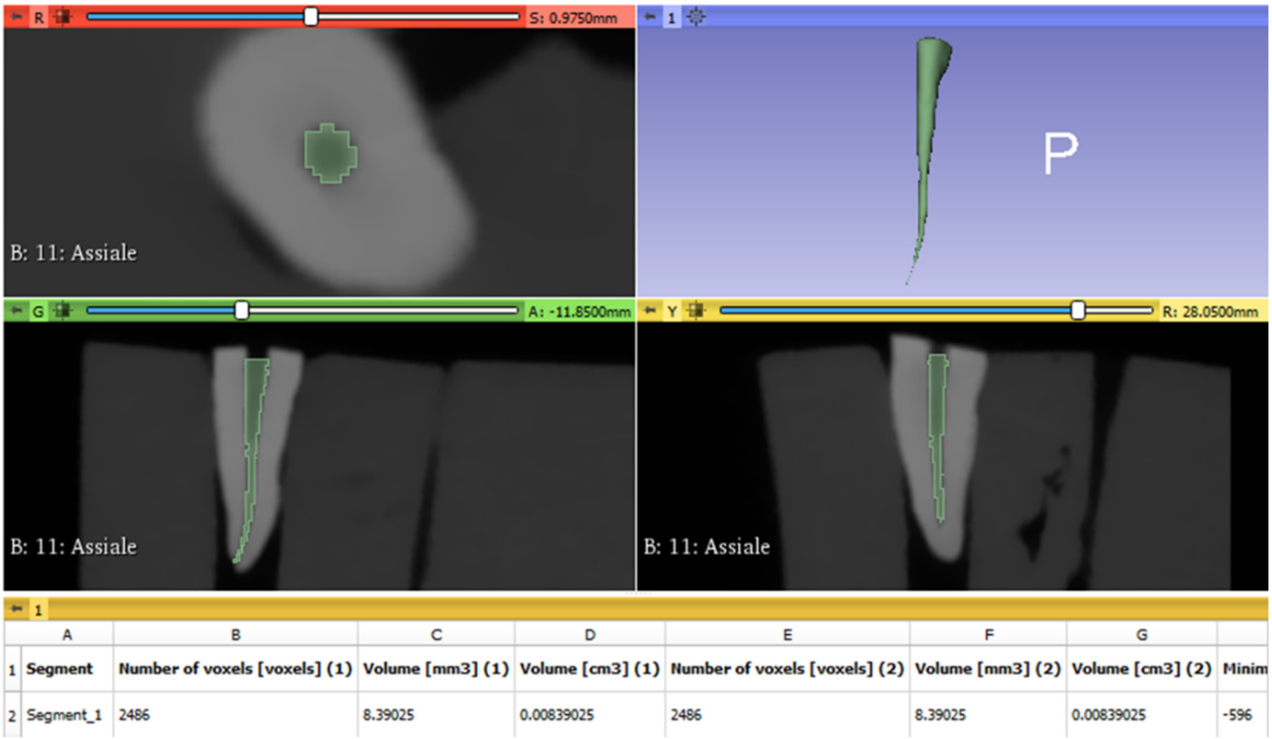
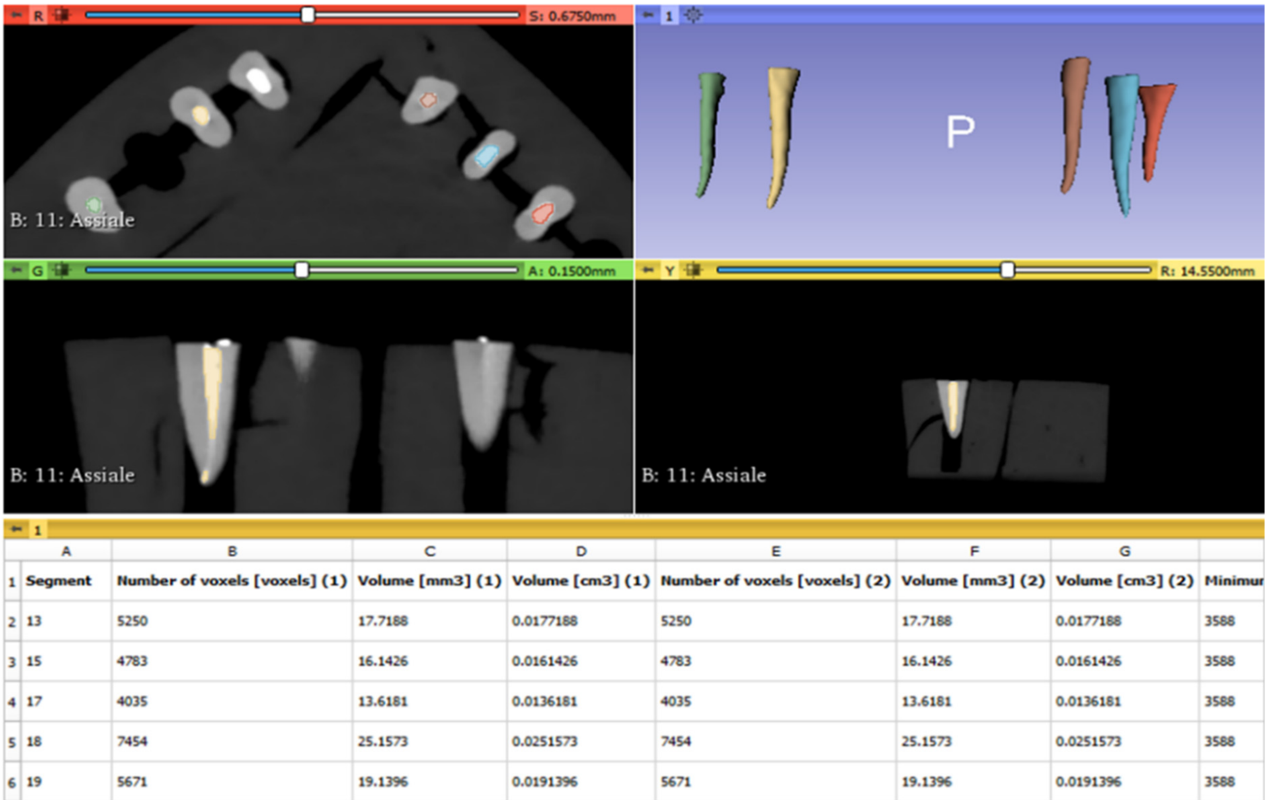
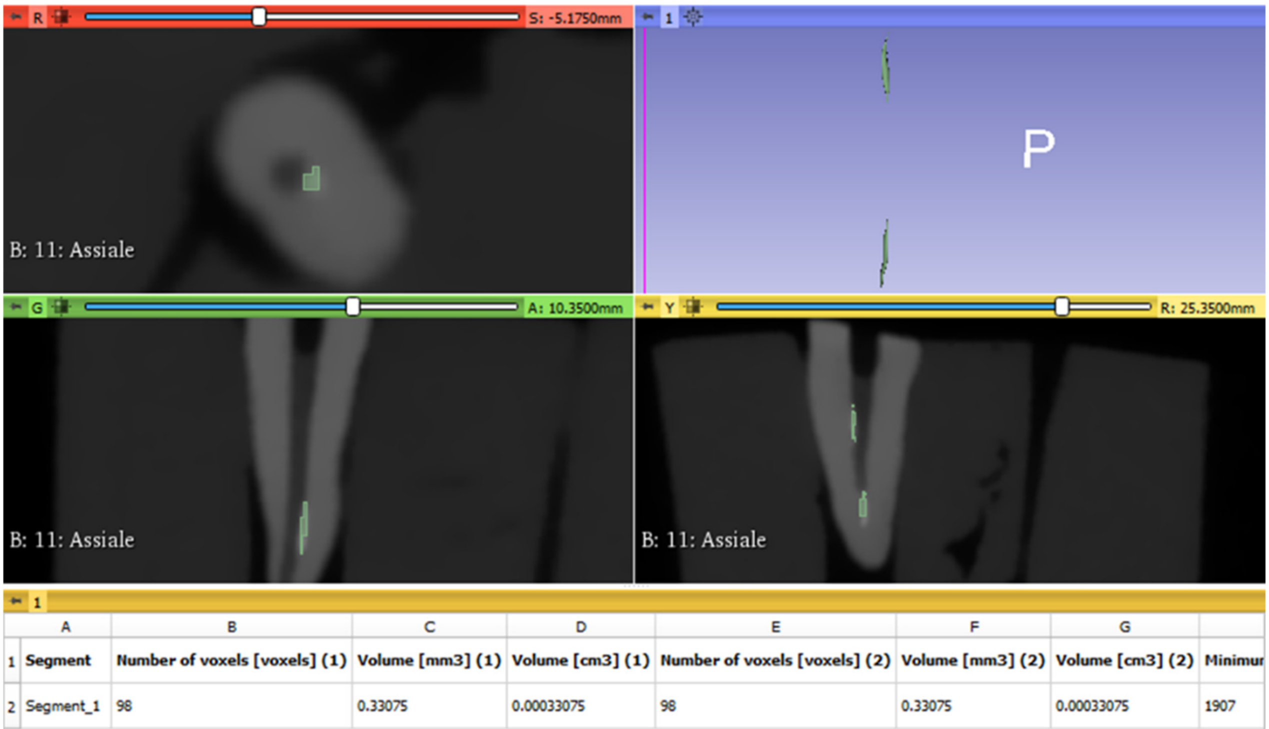


Figure 4. Methodology for quantitative analysis of the canal volume and residual canal volume using Slicer 3D software on CBCT images: post root canal shaping.



	A	B	C	D	E	F	G	
1	Segment	Number of voxels [voxels] (1)	Volume [mm3] (1)	Volume [cm3] (1)	Number of voxels [voxels] (2)	Volume [mm3] (2)	Volume [cm3] (2)	Minimur
2	13	5250	17.7188	0.0177188	5250	17.7188	0.0177188	3588
3	15	4783	16.1426	0.0161426	4783	16.1426	0.0161426	3588
4	17	4035	13.6181	0.0136181	4035	13.6181	0.0136181	3588
5	18	7454	25.1573	0.0251573	7454	25.1573	0.0251573	3588
6	19	5671	19.1396	0.0191396	5671	19.1396	0.0191396	3588

Figure 5. Methodology for quantitative analysis of the canal volume and residual canal volume using Slicer 3D software on CBCT images: immediately after obturation.



	A	B	C	D	E	F	G	
1	Segment	Number of voxels [voxels] (1)	Volume [mm3] (1)	Volume [cm3] (1)	Number of voxels [voxels] (2)	Volume [mm3] (2)	Volume [cm3] (2)	Minimur
2	Segment_1	98	0.33075	0.00033075	98	0.33075	0.00033075	1907

Figure 6. Methodology for quantitative analysis of the canal volume and residual canal volume using Slicer 3D software on CBCT images: after retreatment procedures with RB40.

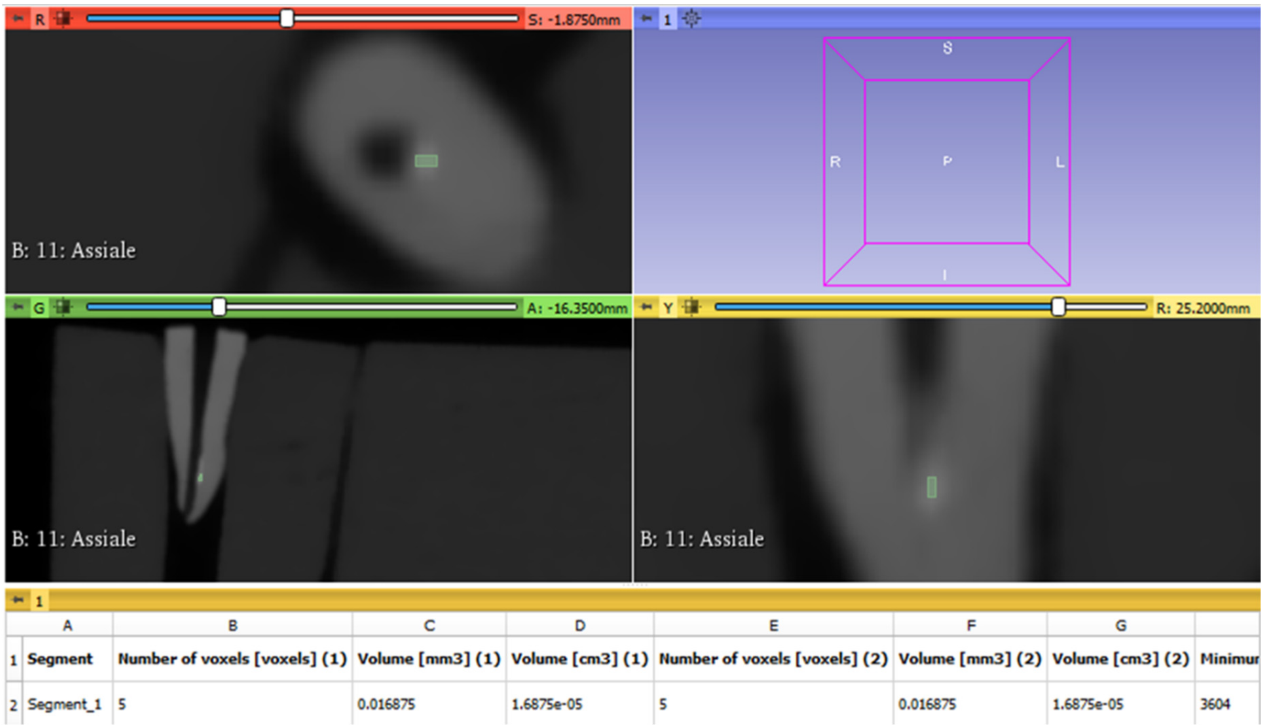


Figure 7. Methodology for quantitative analysis of the canal volume and residual canal volume using Slicer 3D software on CBCT images: after retreatment procedures with RB50.

A

B

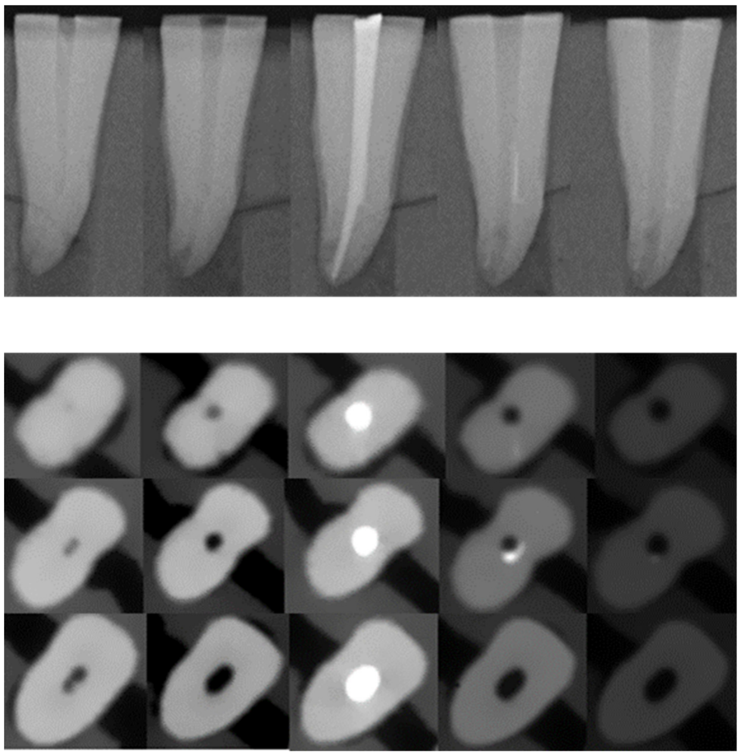


Figure 8. (**A**) Sequence of X-ray images: preoperative, post-instrumentation, at the end of canal obturation, after retreatment with RB40, and after retreatment with RB50. The sample was positioned in the same slot of the customized model made of polyvinylsiloxane after storage at controlled temperature and humidity. (**B**) Sequence of axial sections obtained from CBCT images at 3 mm, 6 mm, and 9 mm from the apex: from left to right, preoperative image, post-instrumentation, at the end of canal obturation, after retreatment with RB40, and after retreatment with R350.

2.5. Statistical Analysis

The normality of each variable was confirmed using the Shapiro–Francia *W′* test and the normal Q–Q plot. All data were summarized as means, standard deviations (SDs), and 95% confidence intervals (95% CIs). Comparisons between obturation techniques were performed using the two-sample *t*-test.

A power analysis was conducted to ensure an adequate sample size to detect a statistically significant mean difference between the areas of the two groups. Assuming an effect size of 0.5 mm^2, a shared standard deviation of 0.4 mm^2, an alpha level of 0.05, and a power of 0.80, the minimum number of teeth required was determined to be 24, that is, 12 per group. Previous studies used a similar methodology and a similar number of teeth per group [13,17].

The agreement between areas measured on the X-rays (mm^2) and volumes obtained through digital reconstruction of CBCT images (^{3}) was summarized with the Pearson linear correlation coefficient *r*. To test for systematic differences between obturation techniques, group-specific *r* coefficients were transformed using the hyperbolic arctangent transformation (Fisher's *z*-transformation) to ensure normalization and variance stabilization [18]. All data were analyzed with Stata 18 (StataCorp. 2023. Stata Statistical Software: Release 18. College Station, TX, USA: StataCorp LLC). The significance level was set at 0.05, and all tests were two-tailed. Missing values were handled using pairwise deletion, resulting in an available-case analysis.

3. Results

Table 1 shows the variation in the canal area. The area increased in both groups without significant differences between them ($p > 0.05$). For the SC group, the increase in the area after instrumentation with Rotate 25.06 was 33.63% (from 5.65 mm^2 to 7.55 mm^2). After root canal obturation, this was 7.15% (from 7.55 mm^2 to 8.09 mm^2). For the GF group, the increase in the area after instrumentation with Rotate 25.06 was 40.0% (from 5.2 mm^2 to 7.28 mm^2). The increase after root canal obturation was 8.39% (from 7.28 mm^2 to 7.89 mm^2).

Table 1. Root canal area (mm^2) measured on the X-rays, by timing and obturation technique.

Timing	Single Cone (*n* = 11)			Guttafusion (*n* = 12)			Difference		
	Mean	SD	95% CI	Mean	SD	95% CI	Mean	*p*-Value	95% CI
Before instrumentation	5.65	0.99	4.98, 6.32	5.19	1.38	4.31, 6.07	0.46	0.370	−0.59, 1.52
After instrumentation	7.55	1.05	6.85, 8.26	7.28	0.99	6.65, 7.91	0.27	0.531	−0.61, 1.16
After obturation	8.09	0.78	7.57, 8.61	7.89 *	1.05	7.14, 8.64	0.20	0.623	−0.64, 1.04

* Available for 10 out of 12 elements. Abbreviations: SD, standard deviation; CI, confidence interval.

Table 2 shows the variation in the canal volume. The volume increased in both groups without significant differences between them. For the SC group, the increase in the volume after instrumentation with Rotate 25.06 was 44.38% (from 7.03 mm^3 to 10.15 mm^3). The increase in the volume after root canal obturation was 77.07% (from 10.15 mm^3 to 17.98 mm^3).

Table 2. Root canal volume (mm^3) obtained through digital reconstruction of CBCT images, by timing and obturation technique.

Timing	Single Cone (*n* = 11)			Guttafusion (*n* = 12)			Difference		
	Mean	SD	95% CI	Mean	SD	95% CI	Mean	*p*-Value	95% CI
Before instrumentation	7.03	2.65	5.25, 8.81	6.06	1.97	4.81, 7.32	0.97	0.331	−1.05, 2.98
After instrumentation	10.15	2.55	8.44, 11.86	8.75	1.90	7.54, 9.95	1.41	0.146	−0.53, 3.35
After obturation	17.98	4.61	14.88, 21.1	15.80	3.17	13.78, 17.8	2.18	0.196	−1.22, 5.59

Abbreviations: CBCT, cone beam computed tomography; SD, standard deviation; CI, confidence interval.

For the GF group, the increase in the volume after instrumentation with Rotate 25.06 was 44.4% (from 6.06 mm^3 to 8.75 mm^3). The increase in the volume after root canal obturation was 80.57% (from 8.75 mm^3 to 15.80 mm^3).

Table 3 reports the remnant area after retreatment with RB40 and RB50 was measured for both groups. For the SC group, the remnants were 0.47 ± 0.9 mm^2 after RB40 and 0.39 ± 0.8 mm^2 after RB50, representing a reduction of 14.89%. For the GF group, the remnant area was 0.59 ± 0.77 mm^2 after RB40 and 0.18 ± 0.33 mm^2 after RB50, representing a reduction of 69.49%.

Table 3. Residual filling material area (mm^2) calculated on periapical radiographs after retreatment with Reciproc Blue (RB) 40 and 50, by obturation technique.

Reciproc Blue	Single Cone (*n* = 11)			Guttafusion (*n* = 10)			Difference		
	Mean	**SD**	**95% CI**	**Mean**	**SD**	**95% CI**	**Mean**	***p*-Value**	**95% CI**
RB40	0.47	0.90	−0.13, 1.08	0.59	0.77	0.04, 1.15	−0.12	0.752	−0.89, 0.65
RB50	0.39	0.80	−0.15, 0.93	0.18 *	0.33	−0.07, 0.44	0.20	0.485	−0.40, 0.81

* Available for 9 out of 10 elements. Abbreviations: SD, standard deviation; CI, confidence interval.

Table 4 reports the remnant volume after the retreatment with RB40 and RB50 was evaluated. For the SC group, the remnant volume was 0.63 ± 1.22 mm^3 after RB40 and 0.51 ± 1.16 mm^3 after RB50, representing a reduction of 20.63%. For the GF group, the remnant volume was 0.55 ± 0.91 mm^3 after RB40 and 0.36 ± 0.59 mm^3 after RB50, representing a reduction of 36.36%.

Table 4. Remnants volume (mm^3) obtained through digital reconstruction of CBCT images after retreatment with Reciproc Blue (RB) 40 and 50, by obturation technique.

Reciproc Blue	Single Cone (*n* = 11)			Guttafusion (*n* = 10)			Difference		
	Mean	**SD**	**95% CI**	**Mean**	**SD**	**95% CI**	**Mean**	***p*-Value**	**95% CI**
RB40	0.63	1.22	−0.19, 1.45	0.55	0.91	−0.10, 1.21	0.08	0.868	−0.91, 1.07
RB50	0.51	1.16	−0.27, 1.29	0.36	0.59	−0.06, 0.78	0.15	0.715	−0.70, 1.01

Abbreviations: CBCT, cone beam computed tomography; SD, standard deviation; CI, confidence interval.

Table 5 shows the area of remnants measured in the coronal, middle, and apical thirds after retreatment with RB40 and RB50. For the coronal third, the remnant area for SC was 0 mm^2 after RB40 and remained 0 mm^2 after RB50. For the GF group, the remnant area was 0.01 ± 0.02 mm^2 after RB40 and 0 after RB50. In the middle third, the remnant area for the SC was 0.23 ± 0.43 mm^2 after RB40 and 0.17 ± 0.37 mm^2 after RB50, representing a reduction of 26.09%. For the GF group, it was 0.33 ± 0.55 mm^2 after RB40 and 0.20 ± 0.35 mm^2 after RB50, representing a reduction of 31.3%. In the apical third, the remnant area for the SC group was 0.25 ± 0.47 mm^2 after RB40 and 0.22 ± 0.44 mm^2 after RB50, representing a reduction of 8.33%. For the GF group, it was 0.25 ± 0.28 mm^2 after RB40 and 0.11 ± 0.12 mm^2 after RB50, representing a reduction of 56%.

Table 6a,b shows the comparison of the percentage of remnants after retreatment with RB40 and RB50 (expressed as mean ± SD) between the SC and GF techniques. For the SC group, the percentage of remnant area was 6.2 ± 11.9% after RB40 and 5.10 ± 10.7% after RB50, representing an overall reduction of 17.74%. The percentage of remnant volume was 3.1 ± 5.2% after RB40 and 2.4 ± 4.8% after RB50, representing an overall reduction of 22.58%. For the GF group, the percentage of remnant area was 7.3 ± 9.3% after RB40 and 5.0 ± 8.0% after RB50, representing a reduction of 31.51%. The percentage of remnant volume was 3.0 ± 3.3% after RB40 and 2.0 ± 2.5% after RB50, representing a reduction of 33.3%.

Table 5. Remnants area (mm^2) calculated on periapical radiographs after retreatment with Reciproc Blue (RB) 40 and 50, by third (coronal, middle, and apical) and obturation technique.

Reciproc Blue/Third	Single Cone (n = 11)			Guttafusion (n = 10)			Difference		
	Mean	SD	95% CI	Mean	SD	95% CI	Mean	p-Value	95% CI
RB40									
Coronal	0.00	0.00	0.00, 0.00	0.01	0.02	0.00, 0.03	−0.01	0.048 ‡	−0.02, 0.00
Middle	0.23	0.44	−0.06, 0.52	0.33	0.55	−0.06, 0.73	−0.10	0.637	−0.56, 0.35
Apical	0.25	0.47	−0.07, 0.56	0.25	0.28	0.05, 0.45	0.00	0.991	−0.36, 0.35
RB50									
Coronal	0.00	0.00	0.00, 0.00	0.00	0.01	0.00, 0.01	0.00	0.153	−0.01, 0.00
Middle	0.17	0.37	−0.08, 0.42	0.20 *	0.36	−0.07, 0.48	−0.03	0.835	−0.38, 0.31
Apical	0.22	0.44	−0.07, 0.52	0.11 †	0.12	0.00, 0.22	0.11	0.525	−0.25, 0.48

* Available for 9 out of 10 elements. † Available for 7 out of 10 elements. ‡ p-value $\leq$ 0.05. Abbreviations: SD, standard deviation; CI, confidence interval.

Table 6. (**a**) Percentage of remnant area after retreatment with Reciproc Blue (RB) 40 and 50, by obturation technique. (**b**) Percentage of remnants volume after retreatment with Reciproc Blue (RB) 40 and 50, by obturation technique.

(a)

Reciproc Blue	Single Cone (n = 11)			Guttafusion (n = 10)			Difference		
	Mean	SD	95% CI	Mean	SD	95% CI	Mean	p-Value	95% CI
RB40	6.2	11.9	−1.8, 14.2	7.3	9.3	0.6, 13.9	−1.1	0.822	−10.9, 8.8
RB50	5.1	10.7	−2.1, 12.3	5	8	−0.8, 10.7	0.1	0.977	−8.6, 8.8

(b)

Reciproc Blue	Single Cone (n = 11)			Guttafusion (n = 10)			Difference		
	Mean	SD	95% CI	Mean	SD	95% CI	Mean	p-Value	95% CI
RB40	3.1	5.2	−0.4, 6.5	3	4.5	−0.3, 6.2	0.1	0.958	−4.3, 4.6
RB50	2.4	4.8	−0.8, 5.7	2	3	−0.2, 4.1	0.5	0.798	−3.2, 4.2

Abbreviations: SD, standard deviation; CI, confidence interval.

Table 7 reports the linear correlation between the areas and volumes between the SC and GF group. The SC group showed a significant positive correlation between the areas and volumes after RB40 and RB50. This correlation was not always observed in the GF group.

Table 7. Linear correlation between areas (mm^2) measured on the X-rays and volume (mm^3) obtained through digital reconstruction of CBCT images, overall and by obturation technique.

	All			Single Cone			Guttafusion			Difference		
	n	r	p-Value	n	r	p-Value	n	r	p-Value	n	r	p-Value
After instr.	23	0.35	0.104	11	0.21	0.531	12	0.47	0.120	23	−0.26	0.538
After RB40	21	0.59	0.005 *	11	0.89	<0.001 *	10	0.10	0.776	21	0.78	0.012 *
After RB50	20	0.83	<0.001 *	11	0.96	<0.001 *	9	0.02	0.961	20	0.94	<0.001 *
After RB40 (%)	21	0.63	0.002 *	11	0.94	<0.001 *	10	0.12	0.734	21	0.81	0.002 *
After RB50 (%)	21	0.80	<0.001 *	11	0.99	<0.001 *	10	0.37	0.297	21	0.62	<0.001 *

* p-value $\leq$ 0.05. Abbreviations: CBCT, cone beam computed tomography; RB, Reciproc Blue.

4. Discussion

Endodontic retreatment aims to eliminate previous filling materials and infected dentin responsible for the persistence of bacterial biofilms within the root canal system [19,20]. These pathogenic microorganisms can adhere to root canal surfaces or infiltrate dentinal tubules, particularly when initial instrumentation is inadequate or fails to reach all areas, facilitating their proliferation in unfilled spaces or voids [21]. This scenario highlights the complexity of achieving a systematic cleaning during retreatment, especially in oval-shaped canals where anatomical challenges represent additional challenges [22,23]. Despite the development of advanced instrumentation techniques, irrigant techniques, and devices [24,25], evidence from in vitro studies (radiographic analysis, CBCT, and Micro-CT imaging) suggests the clinical impossibility of completely removing all filling material [17,26,27].

Interestingly, our study reported that some samples from both groups showed very low amounts of remnants that were difficult to observe through X-ray/CBCT imaging. In particular, the percentages of remnants after the complete instrumentation (RB50) were approx. 5% in the area and approx. 2% in the volume of the total obturation (Table 6a, 6b). The high standard deviation values were due to the high number of teeth with no remaining filling material (9 out of 21 teeth) and the low number of teeth with a considerably (>15%) high percentage of filling material (4 out of 21).

Another study using a similar methodology but a different sealer (epoxy resin-based sealer) showed different results [28], with higher amount of radiographically detectable remnants. This is an interesting finding because if the only variable is the sealer, it implies that premixed bioceramic sealers may adhere less to the canal walls, making them easier to remove during retreatment. Additionally, this difference can be attributed to the lower radiopacity of bioceramic sealers compared to epoxy resin-based sealer. The lower radiopacity may result in less residual material able to be detected on radiographic images, potentially leading to an underestimation of remnants. These findings confirm the importance of the sealer physical and chemical properties, such as the adhesion to the root canal dentinal walls and radiopacity, when evaluating their performance in endodontic treatments and retreatments.

The findings presented in Tables 3 and 4 reveal that the remnants detected through both X-ray and CBCT analyses are quantitatively minimal. These data could be explained by analyzing the methodologies used, particularly the decision to decoronate the teeth and the decision to perform an enlargement of the root canal anatomy with a Reciproc file up to 50.05. Decoronation simplifies access to the endodontic system, potentially enhancing the efficiency of removing previous filling materials in the coronal thirds. As observed in Table 5, the presence of remnants in the coronal third is almost absent. This can be attributed to the ease of access to the coronal third and the use of Gates Glidden burs in the initial retreatment phase. This procedure may not fully replicate the typical clinical scenario where intact coronal structures present additional challenges for the removal of remnants. The existing literature shows contrasting data regarding the amount of remnants measured through CBCT and Micro-CT analysis in canals filled with bioceramic sealers compared to epoxy resin-based sealers [11,29,30].

The quantity of remnants identified in this study shows significant differences depending on the type of radiographic analysis performed: two-dimensional examinations on periapical radiographs show no significant differences between the two groups, while the three-dimensional analysis on the CBCT images indicates some differences.

The two-dimensional analysis indicates a slightly higher quantity of remnants in the GF group (30%) compared to in the CS group (20%) after RB40 instrumentation. These findings can be justified by the location of the remnants after retreatment. Periapical radiographs taken in the buccolingual direction may introduce bias in evaluating the amount of remnants present in the canal: there may be an underestimation when the remnants are disposed axially relative to the canal or an overestimation when the remnants remain longitudinal relative to the canal. Interestingly, the middle third of the canal of the GF group appeared as the section most influenced by the presence of remnants after retreatment with RB40. The instrumentation with RB50 led to greater remnant removal in the GF group compared to in the CS group. The nonsignificant but higher amount of remnants in the middle third of the canals obturated with the GF warm technique can be justified by the technique used in relation to the anatomy of the root. The use of a warm technique in an oval canal may lead to the spreading of gutta-percha in the oval sections of the canal, which are more difficult to remove during retreatment procedures. In contrast, remnant removal in the coronal third is facilitated by the use of Gates Glidden burs and the more accessible anatomy, and the apical third physiologically narrows, tending to reduce its oval section. The cold SC technique did not show a greater accumulation of remnants in the middle third. In this technique, remnants were equally distributed in the apical and middle thirds, possibly due to the cold nature of the technique, which reduces the spreading of gutta-percha. As a consequence, the percentage of remaining filling material was lower in the GF group when compared to the CS group after both R40 and R50 instrumentation phases (Table 6).

On the other hand, the CBCT analysis showed that the GF group had a lower amount of remnant volumes after the use of RB40, with a markedly greater remnant reduction after the use of RB50. The CS group shows a reduction in the remnants between RB40 and RB50 of approximately 20%, while the GF group shows a reduction of approximately 50%. This trend can be explained by the different techniques used. Specifically, the single-cone technique requires more sealer compared to the carrier-based technique. The use of a greater amount of sealer during the retreatment procedures can make it more challenging to remove, which may account for the presence of a larger quantity of remnants.

These data are confirmed by another in vitro study (conducted using SEM) that used the same sealer (NeoSealer Flo) but different instrumentation techniques (single-cone technique vs. the warm vertical compaction technique). Indeed, the study reported a greater amount of remnants with the single-cone technique, in agreement with our data [31].

The correlation analysis reported in Table 7 evidenced a significant positive association of the measured remnant areas and volumes in the SC group but a lower association in the GF group. This aspect deserves some consideration. A linear positive correlation should be expected when considering regular (conical) root canals. However, an oval-shaped canal configuration and a non-uniform removal of remnants in the root canal could lead to differences in both the percentages and quantity of remnants detected by the two radiographical analyses. Small remnants detected by bidimensional X-rays in a vestibular–lingual projection could result in higher percentages when observed through three-dimensional investigations.

The differences shown between the X-ray and CBCT imaging can also be attributed to the different resolution of the two types of imaging and to the blooming effect that radiopaque materials (gutta-percha and bioceramic sealers) can cause when subjected to CBCT examination. This phenomenon has been analyzed in the literature by several studies [32–35]. The data in Table 2 show an increase in the volume of the filled canal of up to 100% compared to the instrumented canal, as confirmed by other in vitro studies [33,35]. As observed in the axial sections obtained using CBCT, the filled canal appears larger than the instrumented canal. This finding has important clinical relevance, as it highlights the usefulness of partially removing the filling material before performing CBCT examinations, aiming to reduce the blooming effect and allowing for a more accurate evaluation of the root canal anatomy (including poorly filled lateral canals, potential perforations, or broken instruments).

Premixed bioceramic sealers are gaining clinical relevance due to their biointeractivity, apatite nucleation ability and ease of use [4]. In recent years, several clinical studies have been published, analyzing the outcomes of treatments involving these sealers [5,8,36]. However, there are still no in vivo studies that evaluate their retreatment outcomes. This research gap highlights a significant area for future investigation. Understanding the retreatability of bioceramic sealers is important for developing comprehensive endodontic treatment protocols. The present study contributes to filling this gap by demonstrating (in vitro) the feasibility of retreating bioceramic sealers and achieving complete apical patency [37], suggesting that the use of Neosealer Flo allows for better apical patency during endodontic retreatment compared to other premixed bioceramic sealers. Our data confirm this, as 100% of the samples achieved apical patency during retreatment. The findings led, therefore, to the rejection of the null hypothesis, revealing differences in the treatment outcomes and thereby challenging the initial assumption that there would be no significant difference between the two techniques.

This study has some limitations. First, the decision to decoronate the teeth, while beneficial for improving access and visualization during retreatment, does not correspond to the clinical scenario, where additional challenges such as accessing and cleaning the root canal system are present. Second, while CBCT and X-ray imaging were used to assess the remnants, these imaging modalities have some limitations, such as resolution differences and the potential for the blooming effect, which can affect the accuracy of detecting remnants. Although Micro-CT provides a greater resolution and three-dimensional reconstructions of root canal systems, it was not employed in this study because the aim was to replicate clinically applicable methodologies. Finally, the retreatment procedures were performed 1 month after root canal filling, while clinically, this event may occur after a longer time span (10 or more years). The different aging of the obturation materials could potentially lead to different retreatment outcomes [38].

5. Conclusions

The present study supports the following concepts:

- Reciprocating instruments are able to remove large quantities of remnants from root canals previously filled with premixed bioceramic sealer and different techniques.
- The premixed bioceramic sealer, when used in combination with the carrier-based Guttafusion technique, proved to be more easily removable from the canal compared to its use with the single-cone technique.
- It was possible to perform the retreatment and achieve apical patency in all the samples.

The comparison between the efficacy of phosphor plate X-ray analyses and CBCT in detecting remnants not only provided deeper insight into the optimal imaging modality for assessing endodontic retreatment quality but also closely mirrored clinical practice by utilizing modalities applicable in vivo.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14156444/s1, Figure S1: The customized model is positioned on a radiolucent support. The support has been modified to achieve a repeatable position for housing the customized model. The X-ray tube is placed on a rigid plane in contact with the radiolucent support to maintain a standard distance from the customized model, on which the samples are placed. The same procedure was followed for the CBCT images.

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