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Evaluating the penetration, interfacial adaptation, and push-out bond strength of four bioceramic-based root canal sealers

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Abstract

Background This study evaluated the penetration, interfacial adaptation, and push-out bond strength of four bioceramic-based root canal sealers (iRoot SP, Well-Root ST, C-Root SP, and KP-Root SP).

Methods A total of ninety mandibular first premolar teeth were used in this study, with eighty teeth randomly divided into eight groups ($n = 10$). Four groups were designated for sealer penetration analysis, using each of the four sealers mentioned above mixed with 0.1% rhodamine B and applied using the single-cone technique. Horizontal root sections were prepared at 2 mm (apical), 5 mm (middle), and 8 mm (coronal) from the root apex, resulting in a total of 120 slices. Penetration was evaluated using confocal laser scanning microscopy. The other four groups were used for marginal adaptation analysis, with the same sealers applied without rhodamine B, and adaptation was assessed using scanning electron microscopy on sections prepared at the same depths. The remaining ten teeth were used to evaluate push-out bond strength, with 30 dental slices prepared from the middle third, each drilled with four 1 mm diameter holes and randomly filled with one of the four sealers; bond strength was measured using a universal testing machine.

Results There was no statistically significant difference in the depth and circumference of dentin tubule penetration between different materials ($P > 0.05$). However, the coronal third was significantly higher than the apical third ($P < 0.001$). For iRoot SP, the percentage of dentin tubule penetration circumference at the middle third was significantly higher than that at the apical third ($P < 0.05$). Additionally, Well-Root ST demonstrated superior adaptability for interfacial adaptation than C-Root SP at all the sites ($P < 0.05$). However, the adaptability of iRoot SP was superior to C-Root SP at the coronal and middle thirds ($P < 0.05$). Moreover, the push-out bond strength conformed to the following order: Well-Root ST > iRoot SP > KP-Root SP > C-Root SP, with notable variations ($P < 0.05$).

Conclusion The Well-Root ST sealer demonstrated the best interface adaptation and push-out bonding strength, as well as iRoot SP showed better permeability.

Keywords Bioceramic-based sealer, Penetration, Adaptation, Push-out bond strength

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Background

Root canal therapy is the primary treatment for endodontic and periapical lesions, aiming to effectively control and eliminate infection [1, 2]. The process involves two key steps: root canal preparation and root canal filling [3]. During preparation, the root canal is mechanically shaped and chemically irrigated to remove pathological tissue and bacteria, ensuring proper cleaning and shaping of the canal space [4]. Subsequently, the root canal system is tightly sealed by root canal filling to prevent bacterial reinvasion and to create favorable conditions for periapical tissue healing [5]. Although each stage is critical, the success rate of root canal treatment depends largely on the quality of the final filling [2].

The complex anatomy of the root canal system, including laterally branched root canals, isthmuses, etc [6]., poses a significant challenge to achieving a complete three-dimensional seal. Conventional root canal filling materials, such as gutta-Percha are difficult to fully adapt to the irregular morphology of root canals, which can lead to microleakage and incomplete sealing [7]. To compensate for this deficiency, root canal sealants play an important role in root canal filling as an adhesive that not only can penetrate into dentin tubules, lateral branching root canals, and the tiny gaps between the root canal wall and the filling material [8], but also form a strong bond between the dentin wall and the core filling material, which significantly enhances the sealing effect of the root canal system [9]. This bond improves the tightness of the root canal filling and contributes to the long-term success of the root canal treatment [7].

Root canal sealers, also referred to as root canal filling pastes [8], have experienced significant progress owing to numerous advancements in the field of material science. They are typically classified based on their primary constituents [10], including silicone-based, zinc oxide eugenol-based, resin-based, glass ionomer-based, calcium hydroxide-based, and calcium silicate-based [8]. Among these, calcium silicate-based sealers are often referred to as "bioceramic-based" [11] due to their bioactive ceramic materials. For instance, iRoot SP (Innovative BioCeramix Inc., Canada) exhibits exceptional physicochemical characteristics, optimal curing time, and slight expansion upon setting, which enhances its sealing ability [12, 13]. In addition, these sealers exhibit favorable bioactivity and minimal cytotoxicity [11], making them increasingly used in clinical practice.

However, iRoot SP does not fulfill all the prerequisites of an optimal root canal sealing material [14] owing to its high solubility [11]. To address this, modifications have been made to its composition, and new materials have been introduced, leading to the development of improved bioceramic-based sealers. For example, Well-Root ST (Vericom, Korea) is a tricalcium silicate-based sealer containing bioactive glass, which enhances its bioactivity [15]. However, due to its hydrophilic nature, it requires moisture to complete its setting [16]. C-Root SP (Beijing Saifuite Oral Medical Instrument Co., Ltd., China) incorporates strontium (Sr), which has been shown to influence bone metabolism [17], stimulate osteoblast proliferation and differentiation [18], facilitate stem cell osteogenesis towards differentiation [19], and inhibit the osteoclast activity [20]. KP-Root SP (Guilin Kevin Peter Technology Co., Ltd., China) incorporates calcium silicate nanoparticles into conventional ceramic matrices, which improve its antimicrobial capability and facilitates bone tissue regeneration and repair [21, 22].

The ability of sealers to penetrate dentinal tubules is critical, as certain microorganisms can infiltrate the deeper layers of dentin, leading to persistent infection [23]. One benefit of the root canal sealer is its ability to eliminate any remaining harmful microorganisms in the dentin tubules and effectively prevent bacterial growth [24]. When the sealer penetrates and hardens within the tubules, it forms a physical barrier that entraps any remaining bacteria, thereby preventing their proliferation and contributing to infection control [6, 25]. The permeability of the sealer plays an important role in this process, as it determines the material's ability to infiltrate and fill the intricate spaces within the dentinal tubules. Thereby the sealer establishes a connection between the core filling material and the root canal wall, ensuring a more effective seal [26]. Additionally, good adaptation of the sealer to the root canal wall is crucial for achieving an effective seal [27]. In addition to having good permeability and adaptability, a root canal sealer must also exhibit adequate push-out bond strength [7], indicating its ability to resist displacement when applied to the dentin of the root canal to a considerable degree.

To our knowledge, no experiments have been conducted to evaluate the performance differences of the aforementioned four sealers in terms of dentin tubule permeability, interfacial adaptation, and push-out bond strength. Therefore, this study aims to compare and analyze the performance of these four bioceramic-based root canal sealers in the aforementioned three critical aspects to determine the most effective sealer for clinical use. The null hypothesis of this study posits that there are no significant differences in dentin tubule permeability, interfacial adaptation, and push-out bond strength among the four sealers when applied to root canals. If the null hypothesis is rejected, it would indicate that differences in the composition or particle size of the sealers may lead to variations in their ability to penetrate dentin tubules, adapt to root canal walls, and resist displacement.

Methods

Sample selection

This study was approved by the Ethics Committee of the Affiliated Stomatology Hospital of Nanchang University (Ethics No.20240509/054). A collection of 90 mandibular single-rooted premolar teeth extracted for orthodontic reasons at the Department of Oral and Maxillofacial Surgery of the Affiliated Stomatological Hospital of Nanchang University was collected. All patients provided informed consent before tooth extraction, allowing the use of extracted teeth for research while maintaining anonymity. The selection of the tooth samples was based on the following criteria: the sample teeth had to be fresh, caries-free (healthy teeth) with fully developed roots and closed apical foramina. In addition, the root length had to be greater than 12 mm (all sample teeth were of the same length and size) and the angle of curvature between the root tip and the root had to be less than 10°. The roots were inspected using a stereo microscope (Leica, Germany) to ensure that there were no hidden cracks or fractures. Periapical radiographs of buccolingual and mesiodistal views were used to exclude teeth with multiple canals, root canal bifurcation, calcified root canals, internal and external resorption, root canal curvature, or apical opening [3, 28]. The selected teeth were scraped to eliminate any soft tissue and tartar from the root surfaces, and subsequently disinfected by immersing them in a 3% sodium hypochlorite (NaOCl) solution for a duration of 15 min [29, 30]. The disinfected teeth were subsequently placed in sterile water at a temperature of 4 °C for future utilization, with a maximum storage period of 1 month.

Specimen Preparation

Preparation for penetration and interfacial adaptation analysis

Among the 90 teeth identified, 80 underwent endodontic treatment as described in the following. The coronal portion of each tooth was removed using a water-cooled diamond disc (EXAKT, Germany) near the cementoenamel junction. A #10 K-file (MANI, Japan) was inserted into the root canal to reach the apex, and the working length was determined by reducing the initial length by 1 mm. The task of root canal preparation was carried out by a single endodontist. Once the root canal was cleared using 10# and 15# K-files, nickel-titanium files from the S3 (SANI, China) and BL (B&L, Korea) systems were employed to prepare the canals (10# K-file → 15# K-file → S3: 04/20 → 04/25 → BL system: 04/35 → 04/40 → 04/50) to a final 50#/04 taper. During the preparation process, the apical foramen was maintained patently using a 15# k-file (MANI, Japan). At each instrument change, the root canals were flushed with 2 ml of 3% NaOCl. Finally, 3 ml of 17% EDTA was used to flush out the smear layer for 3 min, followed by a 1-min rinse with saline to ensure complete removal of chelating agents and prevent interference with the bonding process. In order to prevent NaOCl from reacting with EDTA, it is necessary to irrigate root canal with distilled water between the NaOCl and the EDTA rinses [31]. Then, the root canals were dried using sterile paper points (GAPADENT, China).

Preparation for push-out bond strength analysis

The remaining 10 teeth were processed according to methods described in previous studies and detailed procedures were provided below [29, 32]. The coronal and apical portions of the teeth were removed using a water-cooled diamond disc (EXAKT, Germany), leaving behind the complete middle third of the tooth. Subsequently, three slices with a thickness of 1+/-0.1 mm each were cut from each tooth using a hard tissue microtome (EXAKT, Germany). With an accuracy of 0.001 mm, the final thickness of each slice was ascertained utilizing digital vernier caliper (Avenger Products, USA) (Fig. 1a). This process resulted in a total of 30 dental slices. Four tubular holes were drilled into each root slice using a 1 mm cylindrical carbide bur, each hole was then filled with one of the four materials in order to ensure a fair comparison between them as illustrated in Fig. 1b. Standardized holes were drilled in a parallel alignment with the root tubes using vertical drilling frames while maintaining continuous watering. A minimum distance of 1 mm was maintained throughout this procedure between the aperture, the outer dentin, and the wall of the root canal [32]. All specimens were submerged in 3% NaOCl for 15 min after preparation, and were then rinsed with distilled water in order to counterbalance the NaOCl. Following a three-minute immersion in 17% EDTA, the dental slices underwent a one-minute rinsing in saline to eliminate the smear layer [33]. They were subsequently dried using paper points (GAPADENT, China).

Penetration analysis

iRoot SP, Well-Root ST, C-Root SP, and KP-Root SP sealers were marked with 0.1% rhodamine B (Aladdin, China). 40 teeth after endodontic treatment were randomly divided into 4 groups ($n=10$) and obturated with four sealers, respectively. The obturation process employed the single cone technique. The teeth that had been maintained at 100% humidity at a temperature of 37 °C for a period of 2 weeks, allowing the sealer to fully cure. Then, we cut the specimens horizontally using a hard tissue microtome (EXAKT, Germany). Each tooth was sampled by taking a slice at depths of 2, 5, and 8 mm (apical, middle, and coronal) with a thickness of approximately 1 ± 0.1 mm. Polishing samples using silicon carbide sandpaper. Samples were visualised using a confocal laser scanning microscopy (CLSM) (Zeiss, Germany) at

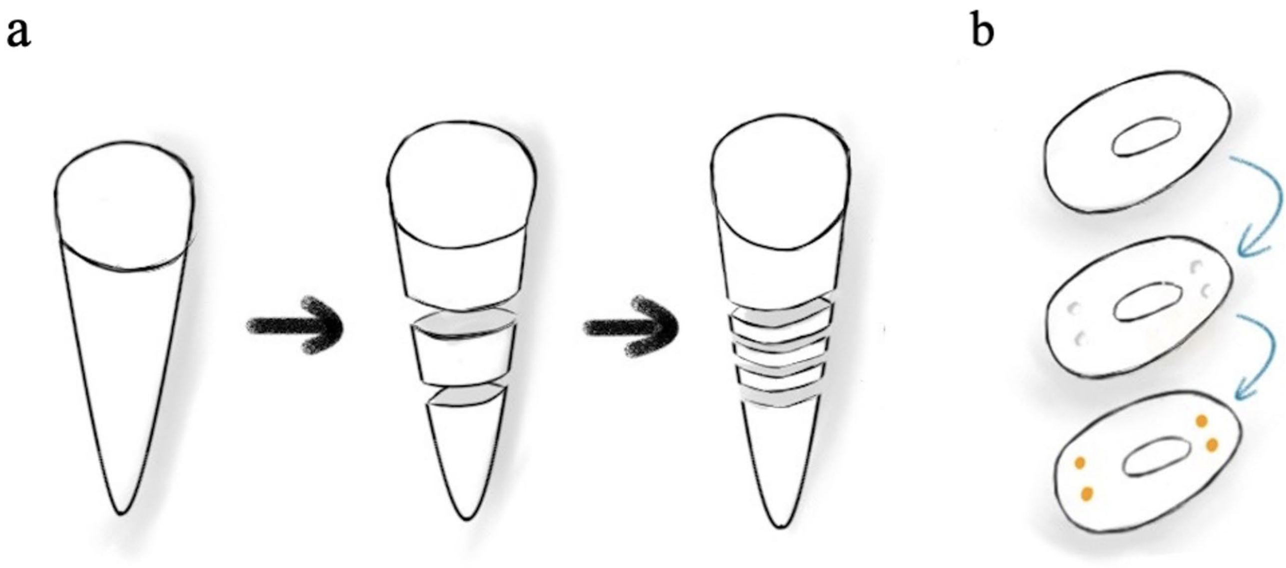

Fig. 1 The experimental schedule of preparing dentin slices and drilling holes. **a** preparation for 3 dentin slices. **b** preparation of four holes in the root dentin, followed by filling the holes with the test sealers

a magnification of 10x, utilizing a wavelength range of 560–600 nm. Since the entire canal could not be examined in a single image, it was combined into a single image using the tile scanning feature. The digital images were imported into the ImageJ program to measure the maximum depth of sealer penetration. This depth was measured as the distance from the root canal wall to the dentin. Additionally, the percentage of sealer penetration circumference into the dentin tubules was measured and calculated [3]. All CLSM images were analyzed and measured by a single operator using ImageJ software, who was blinded to the sealer groups.

Interfacial adaptation analysis

40 teeth after endodontic treatment were randomly divided into 4 groups ($n = 10$) and obturated with iRoot SP, Well-Root ST, C-Root SP, and KP-Root SP sealers, respectively. The obturation process employed the single cone technique. The teeth that had been maintained at 100% humidity at a temperature of 37 °C for a period of 2 weeks, allowing the sealer to fully cure. Then, we cut the specimens horizontally using a hard tissue microtome (EXAKT, Germany). Each tooth was sampled by taking a slice at depths of 2, 5, and 8 mm (apical, middle, and coronal) with a thickness of approximately 1 ± 0.1 mm. The specimens were washed for 2 min in a bath containing 17% EDTA to eliminate organic debris. Subsequently, they were rinsed for 1 min with distilled water. For four hours, the samples were dehydrated in an evaporator. Subsequently, the samples were sputter coated with gold. The samples were photographed using a scanning electron microscopy (SEM) (JEOL, Japan) configured to 5 kV at 500x and 1000x magnification to analyze and quantify the dimensions of the spaces between the adhesive interfaces, as well as to observe the adhesive interfaces between the sealer and the root canal wall and between the sealer and the adhesive. The maximum gap width between the sealer and the root canal wall dentin in each sample was used as the gap width for evaluating the suitability of the sealer. The evaluation criteria described previously was applied [34], and the samples were judged according to following four grades of suitability: good, fair, poor, and no suitability. The following are the reference standards utilized in this study to classify adaptability:

Good: The sample section shows a complete absence of space between the sealant and the dentin of the root canal wall.

Fair: The gap width between the sealer and the dentin of the root canal wall in the sample section is < 1 μm.

Poor: The width of the gap between the sealer and the root canal wall dentin in the sample section ranges from 1 to 10 μm.

No adaptation: The distance between the sealer and the dentin of the root canal wall in the sample section was > 10 μm.

All SEM images were analyzed by 2 calibrated independent observers, who were blinded to the sealer groups. Observer calibration was performed using a set of training images, and inter-observer reliability was assessed using the kappa coefficient, with a threshold of ≥ 0.80 considered substantial agreement. Discrepancies were resolved through discussion to achieve consensus. The level of agreement between the observers was rigorously evaluated, with a kappa coefficient of 0.91, indicating excellent inter-observer reliability.

Push-out bond analysis

A plunger tip with a diameter of 0.8 mm was positioned over the test sealer, ensuring that the surrounding dental structures were not affected. Universal testing machine (INSTRON, USA) was used to apply pressure in the direction of the coronal apex at a rate of 0.5 $mm.min^{-1}$ until the sealer was removed. The load × time curve was plotted in real-time by the software during testing. The tensile strength was quantified and documented in units of MPa. Upon failure, the load, measured in Newtons, was divided by the area of the bonded interface. The area of adhesion of the root canal sealer was determined using the formula: $area = 2\pi r \times h$, where π is approximately 3.14, r represents the radius of the hole to the root canal sealer (0.5 mm), and h represents the height of the material $(1.0\ mm)^3$ [33, 35].

Statistical analyses

The statistical analyses were conducted using SPSS version 27 (IBM). The data's normality was evaluated using the Shapiro-Wilk test. If the data followed a normal distribution, a one-way ANOVA with repeated measures was employed to compare the differences in penetrability, interface adaptability, and push-out bond strength of the four materials and root thirds. Otherwise, a multiple-sample comparison using the Kruskal-Wallis H nonparametric test was used for this purpose. For significant results in the ANOVA or Kruskal-Wallis tests, post hoc analyses were performed to identify specific differences between groups. For normally distributed data, pairwise comparisons were conducted using the Bonferroni correction to control for Type I error. For non-normally distributed data, the Mann-Whitney U test with Bonferroni correction was used for pairwise comparisons. The significance level was set at $\alpha = 5\%$ for all tests, and a p-value less than 0.05 was considered statistically significant.

Results

Penetrability

The Kruskal-wallis analysis demonstrated that the highest level of dentin tubule penetration was observed in the coronal third, followed by the middle third, while the lowest level was observed in the apical third. A notable disparity was observed between the coronal third and the apical third ($P < 0.001$) (Fig. 2a, b). The iRoot SP group exhibited a notable disparity in the proportion of dentin tubule penetration along the perimeter,

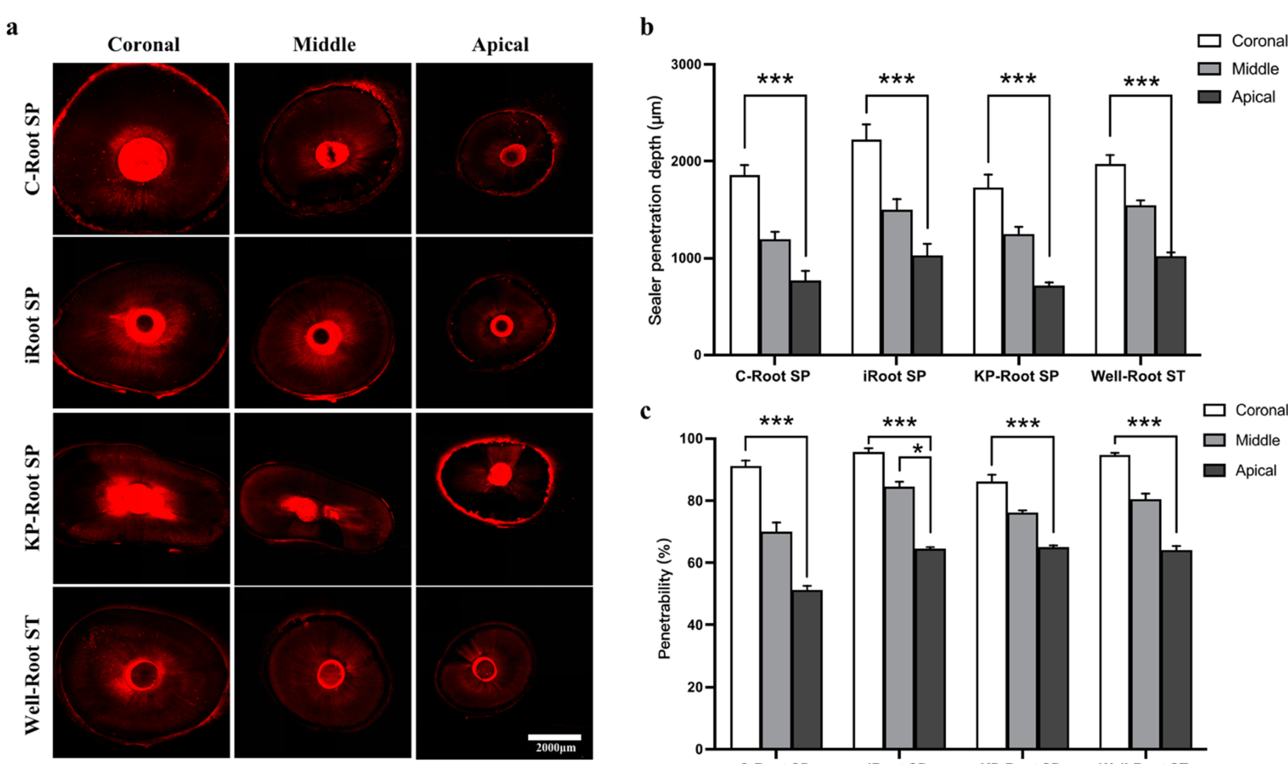

Fig. 2 Evaluation of sealers' penetrability. **a** Representative CLSM images from each group at root canal thirds (coronal, middle, apical) (Scale bar: 2000 μm) (Magnification: 10x). **b** Comparison of the mean values for penetration depth (μm) between sealers at different root canal thirds (coronal, middle, apical). **c** Comparison of the mean penetrability (%) between sealers at different root canal thirds (coronal, middle, apical). *$p < 0.05$ and ***$p < 0.001$

specifically between the middle third and apical third of the root ($P < 0.05$). In addition, there was no statistically significant variation in the depth and percentage of dentin tubule penetration among the remaining test groups at the same locations ($P > 0.05$). Within the test groups, iRoot SP exhibited the greatest extent and proportion of dentin tubule penetration (Fig. 2a, c).

Interfacial adaptation

The representative images of bonding interfaces between the sealers and the root canal walls were shown in Fig. 3. An analysis of the sealers' interfacial adaptation was conducted using image analysis. The level of agreement between different observers was found to be high, with a kappa coefficient of 0.91. Disagreements were resolved through discussion, resulting in an agreement. The outcomes for all the sealers are displayed in Table 1. The Kruskal-Wallis analyses revealed that there was no

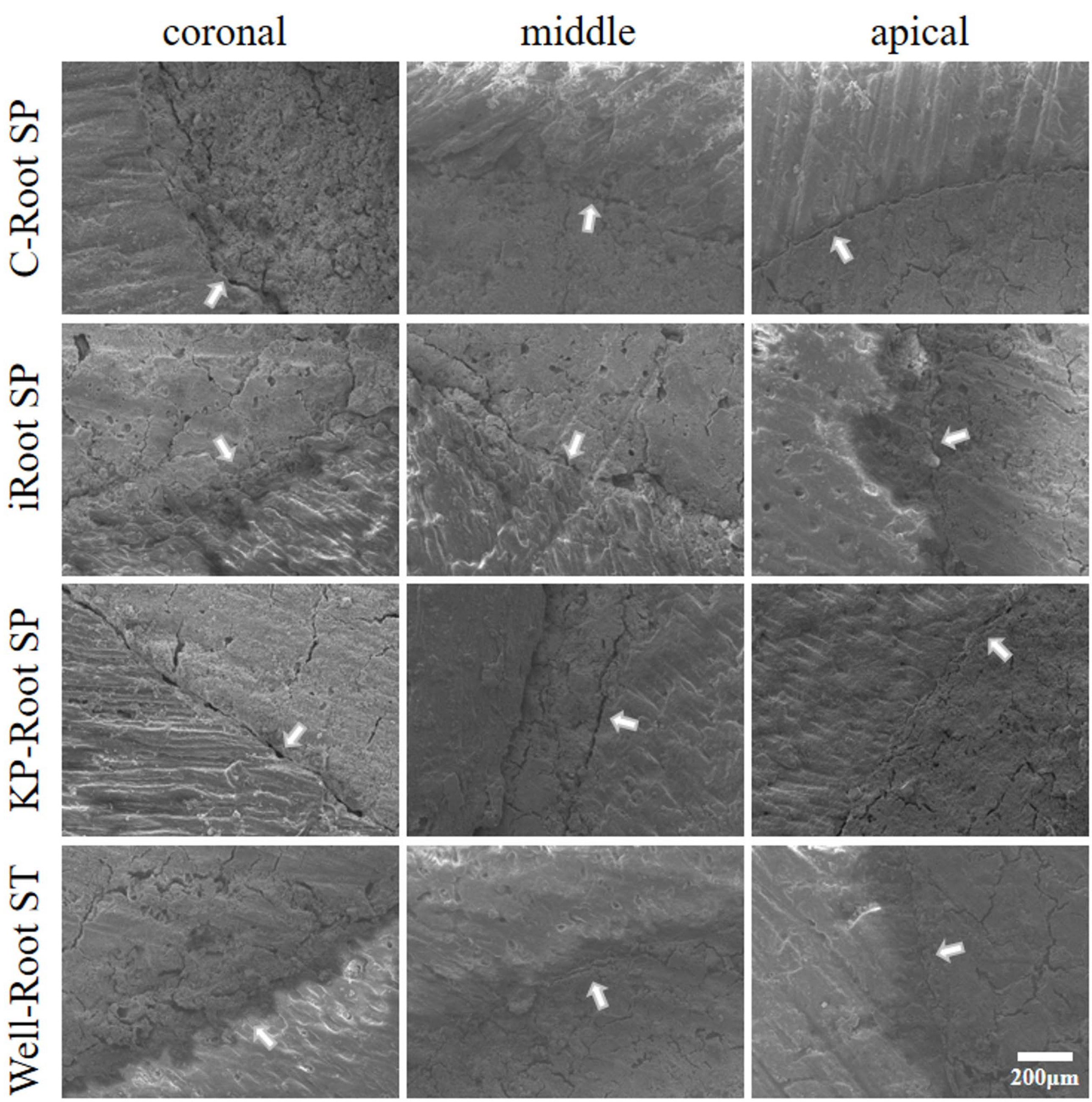

Fig. 3 Evaluation of sealers' interfacial adaptation. Representative SEM images from each group at root canal thirds (coronal, middle, apical) (Scale bar: 200 μm)(Magnification: 1000x). The white arrow indicates the maximum gap between the sealer and the root canal wall dentin in each sample

Table 1 Distribution of sealers' adaptation across the coronal, middle, and apical thirds of the root Canal after obturation

Sealer	Root Canal Third	Good	Reasonable	Poor	No adaptation
C-Root SP	Coronal	0 (0%)	5(50%)	5(50%)	0 (0%)
	Middle	0 (0%)	5(50%)	5(50%)	0 (0%)
	Apical	0 (0%)	9(90%)	1(10%)	0 (0%)
iRoot SP	Coronal	8(80%)	2(20%)	0 (0%)	0 (0%)
	Middle	7(70%)	3(30%)	0 (0%)	0 (0%)
	Apical	7(70%)	3(30%)	0 (0%)	0 (0%)
KP-Root SP	Coronal	2(20%)	8(80%)	0 (0%)	0 (0%)
	Middle	2(20%)	8(80%)	0 (0%)	0 (0%)
	Apical	2(20%)	8(80%)	0 (0%)	0 (0%)
Well-Root ST	Coronal	9(90%)	1(10%)	0 (0%)	0 (0%)
	Middle	9(90%)	1(10%)	0 (0%)	0 (0%)
	Apical	9(90%)	1(10%)	0 (0%)	0 (0%)

Table 2 Descriptive statistics (median, interquartile range and confidence interval) of push-out bond strength values (MPa) for the evaluated root Canal sealers

Material	*N*	Median	IQR	95%CI	*p*-value
C-Root SP	30	0.75	0.25	0.61–0.82	< 0.001
iRoot SP	30	4.71	2.75	4.39–5.43	
KP-Root SP	30	1.58	1.03	1.41–1.61	
Well-Root ST	30	8.72	3.09	7.76–9.11	

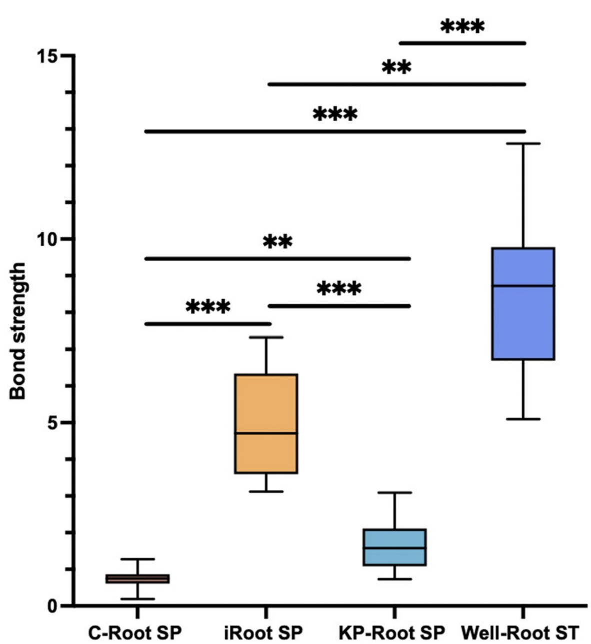

Fig. 4 Evaluation of sealers' push-out bond strength. Box plots illustrating the push-out values (minimum, median, maximum) of the tested sealers. $^{**}p < 0.01$ and $^{***}p < 0.001$

significant variation in interfacial adaptation among each root canal site with same sealers. The Well-Root ST sealer demonstrated superior interfacial adaptation compared to all other sealers. However, when comparing the same sites for each material, there a statistically significant difference between Well-Root ST and C-Root SP was observed at all sites ($P < 0.05$). Additionally, iRoot SP and C-Root SP showed significant differences in the coronal third and the middle third ($P < 0.05$).

Push-out bond strength

The push-out bond strength test results are presented in Table 2. The Well-Root ST exhibited the greatest push-out bond strength, followed by iRoot SP, KP-Root SP, and C-Root SP in decreasing order. In addition, the disparities in push-out bond strength among all groups were statistically significant. Figure 4 displays the visual depiction of the results.

Discussion

Optimal and precise root canal filling can effectively control the infection of complex root canal systems and prevent the reoccurrence of root canal system reinfection [5, 7]. Root canal filling materials can be categorized into two primary types: a solid core material and a sealer [36]. The core material functions as the primary component of the root canal filling, occupying the majority of the root canal system, while the sealer primarily serves to seal off the unique anatomical structures within the root canal and the space between the core material and the root canal wall [2]. Additionally, the sealer acts as a lubricant for the nuclear material during placement [8].

Bioceramic-based root canal sealers are increasingly utilized in clinical settings due to their bioactive properties [37], including biocompatibility, antimicrobial activity, and the ability to promote hydroxyapatite formation. Its swelling properties [12, 23] after curing have led to a shift in root canal filling techniques, with increasing advocacy for the use of sealers as the primary filling material, with gutta-percha being used only to introduce the paste and for retreatment purposes [38]. The single-cone obturation technique [39], often recommended for bioceramic sealers, has demonstrated success rates as high as 90.9% [40]. However, the presence of a smear layer—composed of organic and inorganic debris—can hinder the effectiveness of root-filling materials by harboring bacteria and their by-products [41]. Therefore, the use of chelating agents like EDTA and irrigants such as NaOCl is critical for smear layer removal and enhancing sealer performance [33, 42].

The penetration of root canal sealers into collateral canals, lateral canals, and dentinal tubules is essential for isolating the root canal system from residual microorganisms and debris [25]. This penetration blocks microbial pathways, enhances the sealer's mechanical grip on the core material, and improves overall sealing efficacy [43]. Furthermore, sealer penetration promotes antimicrobial action in the canal, which is further enhanced when it comes into closer contact with microorganisms [5, 24]. The physicochemical properties of sealers, such as particle size, viscosity, and setting characteristics, significantly influence their penetration depth and adaptation [23]. In this study, CLSM was employed to evaluate sealer penetration, as it allows for precise measurement of penetration depth in a moist environment [44]. The sealers were labeled with 0.1% rhodamine B, a concentration that does not alter their physical properties [39, 45].

The results revealed no significant differences in penetration depth or perimeter percentage among the sealers at the same site, suggesting similar penetration capabilities. However, iRoot SP demonstrated superior performance, likely due to its small particle size (< 2 μm) and high viscosity [46], which enhance its ability to infiltrate dentinal tubules. Furthermore, iRoot SP's slight expansion [12]during setting contribute to its effective sealing and penetration. Notably, penetration was highest in the coronal third, followed by the middle and apical thirds, consistent with previous studies [3]. This pattern is attributed to the larger diameter of dentinal tubules in the coronal region [47] and the limited accessibility of irrigation fluid to the apical third [41].

Excellent adaptability of the sealer to the root canal wall is another critical factor for successful root canal treatment [7, 48]. SEM is a widely used technique for evaluating the integrity of material interfaces [49]. In this study, SEM revealed that Well-Root ST exhibited the best adaptation to the root canal wall, followed by iRoot SP and KP-Root SP. On the other hand, C-Root SP exhibited the poorest performance. While all four sealers share a calcium silicate base, variations in their composition percentages and the inclusion of additional ingredients can result in differences in their suitability. In this context, the Well-Root ST includes bioactive glass [16], which helps to maintain the ideal pH level for the creation of hydroxyapatite by releasing soluble Si, Ca, P, and Na ions. The presence of hydroxyapatite-like crystalline labels in dentin tubules facilitates the growth process [50], enabling the Well-Root ST to achieve ideal marginal adaptation.

Root canal sealers must form a strong bond with the dentin wall to prevent reinfection [51]. Push-out bond strength measures the ability of the filling material to resist displacement when applied to root canal dentin [52]. To measure this, a conventional push-out force tester was used, and increasing push-out forces were progressively applied to evaluate the bond strength of the root canal sealers. In this context, Uregan et al. [53] demonstrated that the push-out bond strength is a more accurate measure of bond strength, when compared to conventional shear tests. While the push-out bond strength test may not accurately represent the actual clinical performance of the sealer, it is currently considered the most effective bond test option [54]. Furthermore, unlike numerous other methods, the latest push-out bond strength method was used in this study, it may involve different core materials as well as different dentin preparation procedures [29, 32]. We artificially created standardized root canal structures [33] to compare the bond strength of various root canal sealers. This was done in order to remove confounding variables such as tooth age, root canal shape, hardening, and microhardness in order to maintain a standardized comparison. In order to prevent dental slice fracture, a gap of 1 mm [32] was upheld between each pair of holes, the outer layer of the tooth root, and the inner surface of the root canal. As suggested by Chen et al. [55], the plunger tip size should be smaller than 0.85 times the size of the filling material. Additionally, the plunger tip should be positioned closer to the diameter of the seal. This allows the plunger tip to concentrate stresses in a more focused manner near the interface between the seal and the dentin.

As observed from the findings, the four root canal sealers demonstrated varying bond strengths, with statistically significant distinctions observed between the groups. In this context, the bond strength of Well-Root ST was the highest, while iRoot SP, KP-Root SP, and C-Root SP had progressively lower bond strengths. The high Well-Root ST value may be attributed to the alkaline properties of the hydration products of calcium silicate cement, which degrade the collagen component of interfacial dentin through corrosive action [56]. The degradation results in the creation of a porous structure that allows for the infiltration of high concentrations of Ca^{2+}, OH^{-}, and CO_{32-} ions, resulting in enhanced mineralization in this area [56, 57]. Thus, the micromechanical interactions of this labeled structure enhance the adhesive strength of Well-Root ST. While all the sealers that were tested contained calcium silicate as the primary component, variations in its concentration or the inclusion of other ingredients could potentially affect the outcomes. Furthermore, variations in research methodologies may result in differences in findings between this study and others.

The findings of this study highlight the importance of sealer properties such as permeability, interfacial adaptability, and push-out bond strength in achieving successful root canal treatment. Clinically, the use of bioceramic sealers like iRoot SP and Well-Root ST, which exhibit excellent penetration and adaptation, can enhance the long-term outcomes of endodontic therapy by effectively sealing the root canal system and preventing reinfection. In complex root canal morphologies, such as curved canals, lateral canals, or isthmuses, Well-Root ST may be particularly advantageous due to its superior interfacial adaptation and bond strength. These properties are critical for preventing microleakage and reinfection in anatomically challenging cases. On the other hand, iRoot SP, with its superior permeability, may be preferred in cases where deep penetration into dentinal tubules is essential, such as in teeth with suspected bacterial infiltration into the deeper layers of dentin. While C-Root SP and KP-Root SP showed relatively lower performance in our study, they may still be viable options in less complex cases or when specific properties (e.g., strontium incorporation in C-Root SP for potential osteogenic effects) are desired. Clinicians should consider the specific requirements of each case when selecting a sealer, taking into account factors such as root canal anatomy, the presence of infection, and the desired long-term outcomes.

However, clinicians should consider the limitations of in vitro studies when translating these findings to clinical practice. This study has several limitations that should be acknowledged. First, the study utilized extracted teeth as samples, and variations in the structure of human root canals could pose challenges in standardizing the specimens. Second, the in vitro setup may not accurately reflect the dynamic biological environment of the oral cavity, including the presence of saliva, temperature fluctuations, and occlusal forces. These factors could influence the performance of root canal sealers in clinical settings, potentially limiting the direct translation of our findings to clinical practice. Third, the push-out bond strength test did not incorporate solid core materials, such as gutta-percha, which are commonly used in clinical root canal fillings. This limits the clinical relevance of the bond strength measurements, as the interaction between the sealer and the core material could affect the overall sealing ability. Finally, while our power analysis justified the sample size, a larger sample size could further enhance the reliability and generalizability of our findings. Future studies should aim to address these limitations by incorporating more clinically representative models, such as in vivo studies or simulated oral environments, and evaluating long-term performance under conditions that more closely mimic clinical practice.

Conclusion

The selection of bioceramic-based root canal sealers significantly impacts interfacial adaptation and push-out bond strength. Dentin tubule penetration depth and perimeter percentage varied significantly across root canal positions. Among the tested sealers, Well-Root ST exhibited the best interface adaptation and push-out bond strength, while iRoot SP showed superior permeability. These findings suggest that Well-Root ST may be particularly suitable for complex root canal morphologies, whereas iRoot SP may be preferred in cases requiring deep dentinal tubule penetration.

Abbreviations

Sr strontium
NaOCl sodium hypochlorite
CLSM Confocal laser scanning microscopy
SEM Scanning electron microscopy

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Author contributions
Conceptualization, Y.W. and M.T.; methodology, Y.W.; software, Y.W.; validation, X.Y.; formal analysis, M.T. and X.Y.; investigation, Y.W.; resources, J.Y.; data curation, Y.W.; writing—original draft preparation, Y.W.; writing—review and editing, M.T.; visualization, Y.W.; supervision, J.Y.; project administration, J.Y. and Y.W.; funding acquisition, J.Y. All authors have read and agreed to the published version of the manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
This study was approved by the Ethics Committee of the Affiliated Stomatology Hospital of Nanchang University (Ethics No.20240509/054) and written informed consent was obtained from the participants.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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