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Original Article

A novel bioactive glass-based root canal sealer in endodontics

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Sealing ability

Background/purpose: Bioactive glass (BG), one type of bioceramics, shows similar or better characteristics to calcium silicate which has been regarded as a promising root filling material in endodontics. This study aimed to develop a novel BG-based root canal sealer for endodontics.

Materials and methods: The novel BG-based root canal sealer was composed of phytic acid derived bioactive calcium phosphosilicate glass named PSC mixed with zirconium oxide (ZrO_2) as powder, and phosphate solution (PS) dissolved with sodium alginate (SA) named PS-SA as liquid. Moreover, the physicochemical properties, mineralization, sealing ability and biocompatibility of the novel BG-based root canal sealer were evaluated.

Results: This study developed a novel BG-based sealer named BGS-SA-Zr which contained the powder of PSC and ZrO_2 and the liquid of PS-SA. Results indicated that the flow, film thickness and radiopacity of BGS-SA-Zr conformed to ISO 6876:2012. The setting time and solubility of BGS-SA-Zr were 53.7 ± 1.5 min and $21.46 \pm 0.54\%$, respectively. The pH value of the simulated body fluid (SBF) immersed with BGS-SA-Zr raised slightly up to 7.70. The CCK-8 assay indicated that BGS-SA-Zr had no cytotoxic effects on MG-63 cells. After immersion in SBF for 4 weeks, dense hydroxyapatite crystals were observed on the surface of BGS-SA-Zr. Furthermore, there was no difference in the sealing ability between BGS-SA-Zr and the bioceramic sealer iRoot SP whether setting at 1 day or immersed in SBF for 4 weeks ($P > 0.05$).

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Conclusion: Our results suggest that the novel BG-based sealer may be a promising sealer for endodontic treatment.

Introduction

Sealing the root canal system is one of the keys to successful root canal therapy. The primary functions of root canal sealer are sealing off voids between root canal walls and gutta-percha, embedding residual bacteria and filling irregularities of the root canal system, including small lateral canals and isthmus.[1,2] The criteria for an ideal sealer are as follows: tissue tolerance, no shrinkage with setting, slow setting time, adhesiveness, radiopacity, absence of staining, insolubility to oral and tissue fluids, bacteriostatic properties and ability to create a seal.[3] However, conventional root canal sealers based on zinc oxide eugenol, calcium hydroxide or resins, might have sealing problems due to solubility or polymerization shrinkage after setting, and hence lead to microleakage.[4] In addition, these traditional root canal sealers fail to promote tissue regeneration,[5,6] or even irritate periapical tissues inflammation.[7,8]

Bioceramics, a type of biomaterial, have been introduced as promising endodontic materials for root canal filling owing to their good bioactivities, such as satisfying biocompatibility and expediting the regeneration of periapical tissue.[2,9] A further advantage of bioceramic materials is that they promote the formation of hydroxyapatite (HA), ultimately facilitating a bond between the dentin and the core material after setting.[10,11] It has been reported that a bioceramic root canal sealer, iRoot SP (Innovative Bioceramix, Vancouver, Canada), whose main chemical composition includes calcium silicate, calcium hydroxide and fillers, shows favorable physicochemical and biological properties for root canal sealer and has been commercially available.[12,13] iRoot SP is hydrophilic and can absorb water in root canals or dentinal tubules for hydration reaction and then forms HA.[14] It has been found that iRoot SP has good biocompatibility and can promote osteogenesis in series of researches.[15,16] However, the setting time of iRoot SP is approximately four hours in vitro and even longer when located in the root canal due to less fluid.[11] Faster setting time may be recommended when permanent restorations must be completed quickly or a post must be placed sooner.[17,18] Researchers seem to be elated by the favorable prospect of the bioceramic sealer owing to the bioactive potential and mineralization properties, therefore, it is still important to explore root canal sealers with the high mineralization property, good biocompatibility and fast setting time.[19]

Bioactive glass (BG) which is composed of silicon oxide, calcium oxide and phosphorus pentoxide has higher bioactivity potential comparing to other bioceramic materials accounting for the amorphous structure.[20,21] After implantation, the ions exchange between BG and body fluids can induce the formation of HA through a series of biochemical reactions at the interface, thus forming a firm chemical bond with bones and soft tissues and stimulating tissue repair and regeneration.[19] Recently, BG has been applied to endodontic treatments. It was indicated that a resin-based sealer modified by fluoridated-nano-bioactive glass showed better sealing ability and push out bond strength.[22]

With the advances of material preparation technology, the bioactivity of BG has been improved over time. Recently, phytic acid derived bioactive calcium phosphosilicate glass named PSC with the nominal composition based on feeding ratio of 10.8% P_2O_5, 54.2% SiO_2, and 35% CaO (mol.%) has been developed.[23] When PSC was immersed in simulated body fluid (SBF), the local pH increased slightly, providing a microenvironment with a stable neutral pH for cells survival.[23,24] Studies indicated that PSC could promote the rapid formation of HA in vitro and encourage bone and dental—pulp complex-like tissue regeneration in vivo for its high bioactive potential.[23,25,26] PSC thus seems to be a satisfying material for the root canal sealer in these regards. Therefore, this study aimed to prepare a novel bioactive root canal sealer based on PSC and evaluate their physicochemical properties, sealing ability, biocompatibility in order to explore the feasibility of application in the endodontic treatment.

Materials and methods

Preparation of bioactive glass-based sealers

The BG-based root canal sealers were prepared by mixing powder and liquid. Two kinds of powder for the preparation of root canal sealers were PSC (Wooquick Technology Co., Ltd., Taizhou, China) which was ground through a 400-mesh sieve (pore size, 38.5 μm), and zirconium oxide (ZrO_2, Beijing Deke Daojin Science and Technology Co., Ltd., Beijing, China) with particle size of 10 nm. Phosphate solution (PS) and sodium alginate (SA, Shanghai Aladdin Bio-Chem Technology Co., Ltd., Shanghai, China) were used to prepare the liquid. PS (4 mol/L) was prepared by dissolving dipotassium hydrogen phosphate trihydrate ($K_2HPO_4 \cdot 3H_2O$, Beijing Chemical Works, Beijing, China) and sodium dihydrogen phosphate dihydrate (Beijing Chemical Works) in deionized water, with a pH range of 7.2—7.4. Afterwards, SA with 1% mass volume fraction was dissolved in PS to obtain PS-SA. A mixture of the powder and the liquid was prepared with a powder/liquid ratio (g/mL) of 1.1. Finally, we prepared three types of BG-based root canal sealers named BGS (without ZrO_2 and SA), BGS-SA

Table 1 Chemical composition of bioactive glass-based sealers.

Sealers	Powder		Liquid		Powder/liquid ratio (g/mL)
	PSC (wt%)	ZrO_2 (wt%)	PS (mol/L)	SA (%)	
BGS	100	0	4	0	1.1
BGS-SA	100	0	4	1	
BGS-SA-Zr	70	30	4	1	

Abbreviations: ZrO_2, zirconium oxide; PS, phosphate solution; SA, sodium alginate.

(with SA but without ZrO_2) and BGS-SA-Zr (with ZrO_2 and SA), respectively (Table 1).

Assessment of physicochemical properties

The flow, film thickness, setting time and radiopacity of the BG-based root canal sealers were determined according to the International Standard Organization (ISO 6876:2012).[27]

Flow assessment

0.05 ± 0.005 mL BG-based root canal sealers were separately squeezed onto the center of a glass plate with a dimension of 40 mm and a weight of 20 g. Three minutes later, the second glass plate was placed on the top of the sealer followed by a load of 100 g for 10 min. Subsequently, the load was removed and then the maximum and minimum diameters of the samples were determined to obtain the average diameter which was considered as the flow of the sealer. Each sealer was measured 3 times.

Film thickness assessment

BG-based root canal sealers were placed between two 5-mm-thick glass plates with a size of 200 ± 25 mm^2, respectively. After 180 ± 10 s from the start of mixing, a load of 150 N was applied vertically on top of the glass plate, ensuring each root canal sealer filling the entire area between the two glass plates. After 10 min from the start of mixing, the thickness of the combined glass plates was measured by using a micrometer caliper (Dongguan Kuaijie Measuring Tool Instrument Co., Ltd., Dongguan, China). The difference in thickness of the two glass plates with and without sealers was determined as film thickness. Each sealer was measured 3 times.

Setting time assessment

BG-based root canal sealers were filled separately into gypsum molds with an inner diameter of 10 mm and a height of 2 mm and then incubated at 37 °C and 95% relative humidity for 2 min. The setting time was recorded as the time from the end of mixing to the time when the penetrometer (Beijing Haidian Metrology and Testing institute, Beijing, China) with a weight of 100 g and a diameter of 2 mm failed to make a visible indentation on the surface of the sample. Each sealer was measured 3 times.

Solubility assessment

Six polytetrafluoroethylene cylinders with an inner diameter of 7.75 mm and a height of 1.5 mm were fully filled with BG-based root canal sealers with a waterproof nylon thread placed inside each sealer, respectively. After incubated at 37 °C and 95% relative humidity for 24 h, the BG-based sealers were removed from the mold and weighed (m_1) with an accuracy of 0.001 g. Then samples of each sealer were suspended in a container of 7.5 mL milli-Q water by the nylon thread and placed in an incubator at 37 °C and 95% relative humidity. Seven days later. The samples were removed from the incubator and followed by gently rinsing with deionized water and dried at 60 °C. After drying for 24 h, the samples were reweighed (m_2). The solubility of the BG-based root canal sealers was calculated using the formula: $(m_1\text{-}m_2)/m_1{}^{*}100\%$.

Radiopacity assessment

The gypsum molds with an inner diameter of 5 mm and a height of 1 mm were fully filled with BG-based root canal sealers, and then samples were cultured in an incubator at 37 °C and 95% relative humidity for 24 h, respectively. An aluminum (Al) wedge with a thickness of 0.5–6 mm was employed as the contrast standard reference. Subsequently, 3 digitized images of each sealer with aluminum wedge placed on the occlusal radiographic films were taken by an X-ray unit (INTR, Soredex, Tuusula, Finland) with focus-film distance of 30 cm. Afterwards, the ImageJ 1.51 software (National Institutes of Health, Bethesda, MD, USA) was used to determine the grey pixel values of the sealers and Al wedge on the images, and a graph of thickness of Al against grey pixel values on the radiograph was plotted with the best-fit trend line. Based on the as-obtained equation, the radiopacity of the sealer was expressed in millimeters of Al (mm Al) by comparing the grey values of samples and calibrated Al wedge.

pH value

Polytetrafluoroethylene cylinders was used to shape the BG-based sealers into disks with 5 mm in diameter and 2 mm in thickness. Five specimens of each sealer were prepared. Each specimen was immersed in 5 mL SBF incubated at 37 °C and 95% relative humidity for 1 and 4 h (h), 1, 2, 3, 7, 14, 21 and 28 days (d). Then the pH of the solution was measured by the pH meter (PHS–3C, Shanghai Yueping Science Instrument Co., Ltd., Shanghai, China).

Assessment of biocompatibility

To evaluate the biocompatibility of BG-based root canal sealers, cell counting kit–8 (CCK-8, DOJINDO, Shanghai, China) was used to observe the effect of materials on the proliferation of mouse osteosarcoma MG-63 cell line. Firstly, 5 cylindrical samples of every sealer with a diameter of 5 mm and a height of 2 mm were immersed in Dulbecco's modified eagle medium (DMEM, Gibco BRL, Gaithersburg, MD, USA) with shaking at 120 rpm and 37 °C for 3 days, respectively. Subsequently, the supernatant was collected through filter membrane under sterile conditions. About 200 μL of MG-63 cell suspensions with the cell density of 3×10^3 cell/ml were seeded in each hole of 96-well plates and cultured in an incubator at 37 °C with 5% CO_2 for 1 day. Then the culture medium was drawn out and replaced with 100 μL extracts of different dilution ratio every 2 days. MG-63 grown directly in DMEM were used as the control group. After culturing for 1, 2

and 3 days, the optical density (OD) values at 450 nm were determined by CCK-8 assay.

Assessment of mineralization and sealing ability

Specimens' preparation

Single-rooted mandibular anterior teeth with completely formed roots and closed apices which were approved by the Ethics Committee, School and Hospital of Stomatology, Peking University (PKUSSIRB-202053006) were cleaned by using curettes to remove the attached soft and hard tissues, and then self-curing resin was used to embed these teeth. Subsequently, each specimen was sectioned horizontally using a low-speed diamond cutting machine (SYJ-150, Shenyang Kejing Auto-instrument Co., Ltd., Shenyang, China) to obtain 12 horizontal root sections of 1 mm thick. The thicknesses of the sections were checked using a digital caliper. All specimens with cracks or structural anomalies under stereoscope (ZOOM-630 E, Shanghai Changfang Optical instrument Co., Ltd., Shanghai, China) were discarded, and finally 124 specimens were collected. The surfaces of dentin discs except the root canal were coated with nail varnish. After nail varnish dried completely, a round bur was used to drill a hole with a diameter of 1 mm in the root canal center of each dentin discs. The prepared discs were soaked in 2.5% NaClO for 3 min and 17% EDTA for 3 min.

Assessment of mineralization

The 16 specimens were used for the assessment of mineralization. Totally 8 specimens filled with BG-based root canal sealers and iRoot SP were placed in an incubator at 37 °C and 95% relative humidity for 1 day. Then another 8 specimens filled with the three sealers were soaked in SBF which was refreshed every 2 days for 28 days. After 1-day setting or 28-day incubation, these specimens were placed in a dryer at 60 °C for 3 days. All samples were sputter-coated with gold and then their surface morphologies were viewed under a scanning electron microscope (S-4800, Hitachi, Tokyo, Japan).

Assessment of sealing ability

The left 108 specimens were divided into 12 groups for the assessment of sealing ability. Nine specimens of each group were filled with BGS, BGS-SA, BGS-SA-Zr and iRoot SP, respectively, which were incubated at 37 °C and 95% relative humidity for 1 day, respectively. Nine unfilled specimens without being coated with nail varnish were recognized as the positive group and 9 unfilled roots coated with nail varnish were recognized as the negative group. As described above, another 6 groups were prepared and soaked in SBF for 4 weeks which was refreshed every 2 days. All specimens were soaked in 0.5% methylene blue solutions. One day later, specimens were rinsed with running water for 30 min, and then the sealers and nail varnish were removed. After this, each specimen was replaced in a 1.5 mL EP tube and soaked with 65 wt.% salpeter solution for 1 day and then the supernatant was collected. 200 μL of supernatant and 65%wt salpeter solution was added in each hole of 96-well plates, respectively. The salpeter solution was referred as blank group. Finally, the optical density (OD) values at 550 nm were measured using a spectrophotometric microplate reader (ELX808, BioTek, VT, USA). The OD percentage of each group relative to the OD of the positive control group was calculated separately.

Statistical analysis

Quantitative data were summarized as mean ± standard deviation (SD) and analyzed using one-way analysis of variances (ANOVA). All analyses were conducted with the SPSS 24.0 software (IBM, Chicago, IL, USA). Differences with $P < 0.05$ were considered statistically significant.

Results

Physical properties

As can be seen in Fig, 1, BGS appeared as a bright uniform but thin non-viscous paste. BGS-SA and BGS-SA-Zr presented as pastes with high consistency, strong viscosity, bright appearance, and uniformity. The physical properties of BG-based sealers are shown in Table 2. According to the flow test and film thickness test, three BG-based sealers showed good flow greater than 17 mm and film thickness lower than 50 μm, which conformed to the ISO 6876:2012 recommendations. The flow and thickness of BGS and BGS-SA-Zr were similar ($P > 0.05$), but better than the flow of BGS-SA and thinner than the film thickness of BGS-SA ($P < 0.05$). The setting time of BGS-SA-Zr was longer than that of BGS-SA ($P > 0.05$) and shorter than that of BGS ($P < 0.05$). The solubility of BGS-SA and BGS-SA-Zr were 22.79 ± 1.64% and 21.46 ± 0.54%, respectively, which was lower than that of BGS. BGS-SA-Zr exhibited good radiopacity which met the recommendation of ISO 6876:2012 specifications (3 mm Al), whereas BGS and BGS-SA failed to reach the ISO requirement.

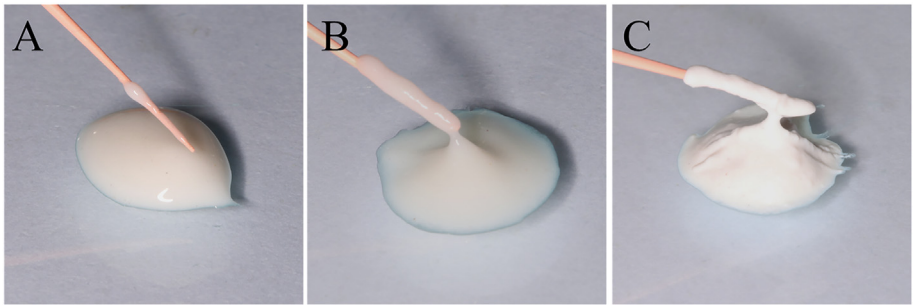

Figure 1 Pastes of (A) BGS, (B) BGS-SA and (C) BGS-SA-Zr spatulated for 1 min.

Table 2 Physical properties of bioactive glass-based sealers.

Sealers	Flow (mm)	Film thickness (μm)	Setting time (min)	Solubility (%)	Radiopacity (mm Al)
BGS	18.58 ± 0.14^{a}	45.3 ± 0.6^{a}	68.0 ± 2.0^{a}	26.43 ± 0.86^{a}	1.11 ± 0.04^{a}
BGS-SA	17.58 ± 0.14^{b}	47.7 ± 0.6^{b}	46.8 ± 1.6^{b}	22.79 ± 1.64^{b}	1.08 ± 0.06^{a}
BGS-SA-Zr	18.25 ± 0.25^{a}	45.3 ± 0.6^{a}	53.7 ± 1.5^{c}	21.46 ± 0.54^{b}	3.23 ± 0.11^{b}

Different superscript small letters in the same row represented statistically significant difference among the materials ($P < 0.05$).

pH and biocompatibility

The pH values of SBF immersed with BG-based sealers are shown in Fig. 2A, respectively. The pH values of SBF immersed with BGS, BGS-SA and BGS-SA-Zr increased slightly up to 7.64, 7.72 and 7.70 from 1 hour to 21 days, and then tended to be stable.

The CCK-8 assay of MG-63 cells cultured in extracts of BG-based sealers were presented in Fig. 2B. Results indicated that the number of MG-63 cells increased continually for 3 days. At the first day, the OD values of BGS and BGS-SA were similar to that of the control group, and the OD value of BGS-SA-Zr was significantly higher than that of the control group ($P < 0.05$). At the second and third day, the OD values of BG-based sealers were lower than that of the control group, whereas there was no significant difference among them ($P > 0.05$).

Mineralization

As shown in Fig. 3, the surface structures of BG-based sealers and iRoot SP after setting at 1 day and immersion in SBF for 4 weeks were analyzed by SEM. After setting at 1 day, there was no obvious mineral deposits on the surface of BG-based sealers and iRoot SP (Fig. 3A, C, E and G). Fig. 3B, D, F and H showed that dense hemispherical and plate-like HA crystals were observed on the surface of BG-based sealers and iRoot SP.

Sealing ability

Fig. 4A and B were the stereomicroscopic images of models stained with methylene blue from different groups after setting at 1 day and immersion in SBF for 4 weeks, respectively. The positive control group (unfilled with sealers and uncoated with nail varnish) exhibited the deepest dye penetration depth, while the groups of BG-based sealers and iRoot SP exhibited the shallower dye penetration depth, and there was almost no staining appeared in the models of the negative control group (unfilled with sealers but coated with nail varnish). The results of semi-quantitative analysis of methylene blue stained samples after setting at 1 day and immersion in SBF for 4 weeks showed that there were no statistical difference among the OD percentage of BGS-SA, BGS-SA-Zr and iRoot SP ($P > 0.05$), but higher than that of the negative control group ($P < 0.05$) and lower than that of BGS and the positive control group ($P < 0.05$); The OD percentage of BGS was significantly lower than that of the positive control group and higher than that of the negative control group (Fig. 4C and D).

Discussion

BG is a kind of material with good bioactivity. When immersed in body fluid or SBF, Ca^{2+} in BG was exchanged with H^{+} in the solution and then Si–O–Si bonds were broken, which promoted the formation of a SiO_2-rich layer at the glass–solution interface. After that, Ca^{2+} and PO_4^{3-} in solutions migrated to the surface and then hydroxyapatite was formed.[28] PSC is a novel pH-neutral calcium phosphosilicate bioactive sol–gel glass.[29] In the sol–gel preparation process, the heat treatment temperature can be reduced to 500°C–700 °C, whereas the specific surface area and releasing rates of ions can be increased.[23] Phytic acid was non-toxic and could be fully mixed with calcium when used as the precursor, which could promote calcium

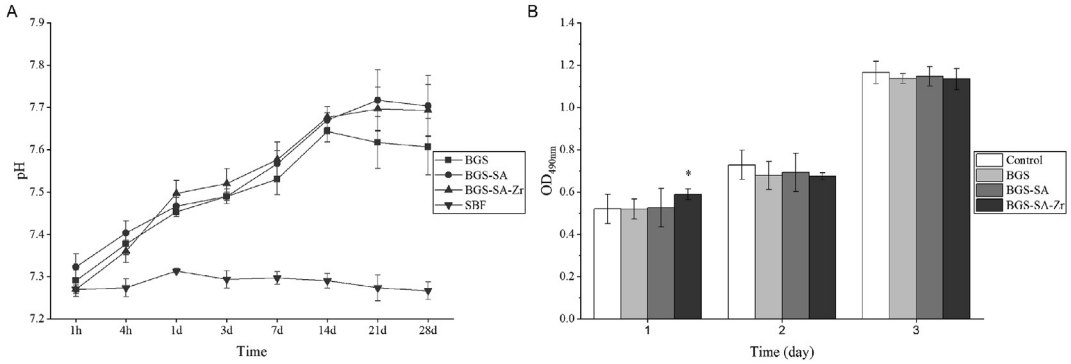

Figure 2 (A) pH value change of SBF immersed with bioactive glass-based root canal sealers at different time. (B) Viability of MG-63 cells with extracts from bioactive glass - based root canal sealers at different time. * represented statistically significant difference compared with the control group.

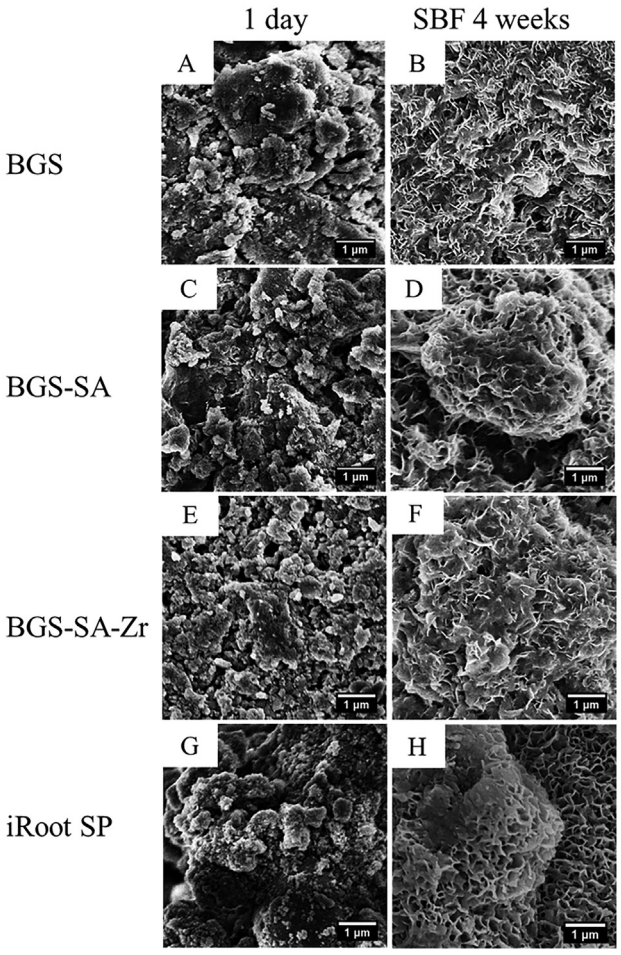

Figure 3 Micrographs of surfaces of bioactive glass-based root canal sealers and iRoot SP (A, C, E, G) after setting at 1 day and (B, D, F, H) immersion in SBF for 4 weeks.

ions to enter the silicon atom network and remove the byproduct of toxic nitrate ion, therefore PSC had less toxicity and significantly improved biocompatibility.[23,24,29] In addition, the improvement of preparation technology made the phosphorus component of PSC much higher than that of conventional BG, hence PSC could release large amounts of soluble silicate ions and phosphate ions quickly, which presented a neutral pH value and formed HA on its surface rapidly and strongly.[23,25,30] The previous evidence had indicated that HA can form more rapidly when PSC was soaked in SBF compared with the classical 45S5 bioglass.[25] Furthermore, PSC could better promote the proliferation, migration and mineralization as well as the osteogenic and angiogenic differentiation of bone marrow mesenchymal stem cells (BMSCs) than 45S5 bioglass and beta-tricalcium phosphate (β-TCP).[26] The aim of this study was to prepare a root canal sealer with good performance utilizing the favorable mineralization property and biocompatibility of PSC. The addition of small amounts of organic polymers, such as sodium alginate, could significantly improve the cohesiveness, anti-washout property and injectability of BG and did not affect the property of mineralization.[31,32] Previous studies indicated that when mixed with sodium alginate, the anti-washout resistance, formability and injectability of tricalcium silicate were improved, and the setting time of the material might be shortened.[33–35] Appropriate radiopacity is an essential requirement for root canal sealers. ZrO_2, a commonly used radiopacifier, had no cytotoxicity and didn't stain teeth as well.[36,37] For these reasons, three novel BG-based sealers were prepared by mixing BG with or without ZrO_2 nanoparticles and the phosphate solution with or without sodium alginate, and the physicochemical properties, biocompatibility, mineralization ability and sealing ability were evaluated to explore the feasibility of application in the endodontic treatments.

The high flow enabled sealers to reach the root canal systems difficult to reach, such as the lateral canals and

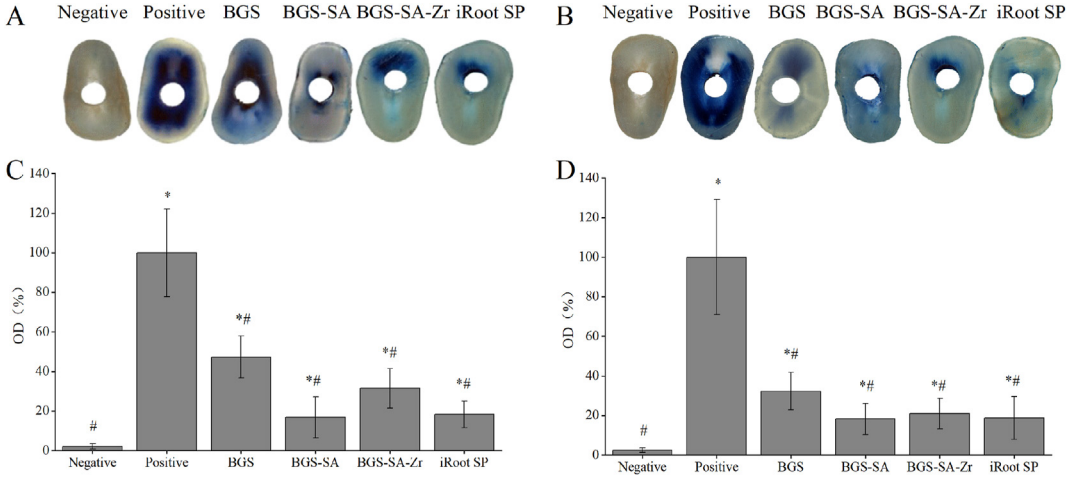

Figure 4 Dye leakage model of different sealers after (A) setting at 1 day and (B) immersion in SBF for 4 weeks; Semi-quantitative analysis of methylene blue of dentin discs obturated with different sealers after (C) setting at 1 day and (D) immersion in SBF for 4 weeks. * represented statistically significant difference compared with negative Group, # represented statistically significant difference compared with positive group.

isthmus. The smaller film thickness of sealers allowed the root canal to be better filled, which might prevent microleakage due to the shrinkage or degradation of sealers aggregated.[38] In this study, PS-SA was used to prepare root canal sealers, and it was found that the flow was decreased and the film thickness was increased. However, the root canal sealer mixed with SA was more viscous and had a more uniform appearance, which was conducive to clinical use. In addition, results in this study indicated that the introduction of ZrO_2 nanoparticles to the sealer not only increased the radiopacity, but also further improved the flow and decreased film thickness of the sealer.

Appropriate setting time was beneficial to clinical operation and it was important to employed a sealer with short setting time when the permanent restoration should be completed immediately or a post would be placed in the canal immediately, which might decrease the duration and frequency of patient visits.[17,18] For the reason that the composition, particle size, ambient temperature and relative humidity were related to the setting time of materials, and hence this study reduced the particle size of the bioactive glass, increased the concentration of the phosphate solution, and added low concentrations of sodium alginate. As shown in results, we found that the setting time of BG-based sealers was shortened from 68.0 min to 53.7 min by adding ZrO_2 and SA, which was shorter than iRoot SP (2.7 ± 0.3 h) and AH Plus (11.5 ± 1.5 h) reported in the previous literature.[12]

According to ISO 6876:2012, solubility is the mass loss after immersion in water for a period of time, which should not exceed 3% of the initial mass.[27] We obeyed the method of solubility test proposed by Carvalho-Junior in the condition of smaller dimensions for test samples used, which was similar to the solubility test commended by ISO.[39] The results in this study showed that the solubility of BGS was 26.43%, but it declined when ZrO_2 and SA were added to the material. The solubility of BGS-SA and BGS-SA-Zr was 21% and 23%, respectively, which was similar to the solubility of iRoot SP presented in previous study.[40,41] This might be related to ion release of these kinds of bioactive materials in deionized water.[40] In addition, as shown in the results of sealing ability, BGS-SA and BGS-SA-Zr exhibited good sealing ability.

Sealing ability was one of the most important properties of root canal sealer, which contributed to the success of root canal treatment.[42] Methylene blue staining and semi-quantitative analysis were used in this study, and it was found that, whereas there was no statistical difference in the staining of dentin discs between BGS-SA, BGS-SA-Zr and iRoot SP after setting at 1 day and soaking in SBF for 4 weeks ($P > 0.05$), which demonstrated that the BG-based sealer had good sealing ability. This study further observed the mineralization performance of the materials, and found that a large amount of minerals formed on the surface after immersion in SBF for 4 weeks, which might be the reason for the good sealing performance despite high solubility. After being in contact with tissue fluids, traditional BG or calcium silicate released Ca^{2+}, resulting in increased pH of the surrounding media and inflammatory stimulation to cells in the initial stage.[43,44] In this study, BGS, BGS-SA, and BGS-SA-Zr increased the pH values of SBF slightly up to 7.64, 7.72, and 7.70. This was because PSC contained no sodium and had a relatively high phosphorus content. After being soaked in SBF, the acidic phosphorus substances released could help compensate for the increase in pH caused by the exchange of Ca^{2+} and H^{+}.[45,46] This feature of PSC made it less irritating to tissues and thus had better biocompatibility.[29] In this study, CCK-8 assay was used to further evaluate the cytotoxicity of the BG-based sealers to MG-63, and the results showed that the three BG-based sealers had no cytotoxicity to MG-63, indicating that the BG-based sealers had good biological activity and the addition of sodium alginate and ZrO_2 did not increase the cytotoxicity of the materials.

In this study, a novel BG-based root canal sealer for endodontic treatments was prepared and characterized. This BG-based root canal sealer (BGS-SA-Zr) possessed good flow, appropriate film thickness, radiopacity, and short setting time, which had met the requirements of the ISO standard and shown excellent physical properties and biocompatibility, at the meanwhile it had good mineralization and sealing ability. These results suggested that the novel BG-based root canal sealer could be a potential candidate for endodontic treatments. Future studies focusing on the optimized composition of the BG-based root canal sealer with better bioactivity were warranted.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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