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Biomimetic dentin desensitizer based on nano-structured bioactive glass

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ABSTRACT

Objectives. This study evaluated the ability of a novel sol–gel bioactive glass, in conjunction with appropriate carrier vehicles, to reduce dentinal fluid flow, with an eye toward reducing dentinal hypersensitivity.

Methods. Experiments were conducted to measure the reduction in tubule fluid flow after treatment of cut tooth surfaces with sol–gel bioactive glass particles in several carrier vehicles. Surfaces were also examined after exposure to brushing and acidic solutions. A non-bioactive particulate glass was compared.

Results. Tubular occlusion produced by the bioactive glass was observed via SEM and a sustained reduction in hydrodynamic conductance was measured after exposure to various fluids and brushing.

Conclusions. This new material may be used with the tested carriers to significantly and durably reduce tubule fluid flow, ultimately resulting in reduced dentinal hypersensitivity.

1. Introduction

It has been stated 8–35% of the population in the U.S. at any one time suffers from dentin hypersensitivity [1], but there are estimates as high as 74% [2]. It also has been reported that root sensitivity increases from 9 to 15% pre-periodontal surgery, to 55% post-surgery [3]. In vivo studies provide strong evidence that the sensitivity originates from the exposure of open dentinal tubules at the surface of the tooth [4] and is caused by changes in the local environment, including temperature, pressure, osmolality, and chemical agents. These local environment changes cause fluids in the dentinal tubules to move quickly, stimulating the nerves surrounding the odontoblasts and giving rise to pain as postulated in the hydrodynamic theory [5]. Typical methods to alleviate the effects of dentin hypersensitivity include occluding the open tubules with organic or inorganic chemicals and compounds, as well as applying chemical agents that suppress pain expression [6,7]. The general consensus is that the most effective and durable method for achieving relief would be to seal the dentin surface through tubule occlusion, thereby eliminating or minimizing movement of fluids in the tubules [8].

Various agents have been packaged as both in-office, as well as over-the-counter medicaments for treating tooth hypersensitivity [6]. However, there currently is no ideal system for performing this task. Potassium oxalate, potassium chloride, glutaraldehyde, resin monomers, and other materials have been used either in dentifrices or as single or multiple application agents to occlude dentinal tubules. While these

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materials have been shown to provide some relief, none have been proven to be completely effective. Recently, a bioactive glass has been added to a dentifrice for this express purpose [1]. Tubule occlusion was examined by scanning electron microscopy, and shown to be enhanced to some extent with certain formulations. However, no attempt was made to study the ability of the agent to reduce dentin permeability. The durability of the surface layer also was not studied, though it was suggested that it is easily washed off with water.

Bioactive glasses have been shown to promote the crystallization of new mineral on their surfaces [9–12]. Other studies have verified the precipitation of a calcium phosphate ceramic on the surface of a tooth after application of a bioactive glass (Bioglass®), providing evidence for the potential of this form of treatment [13]. Bioactive glasses can be formulated by the sol–gel process such that they have varying rates of dissolution and mineral formation in biologic environments [14].

The objective of this study was to examine in vitro the dentinal tubule sealing ability of a nano-structured sol–gel bioactive glass preparation delivered on exposed dentinal tubules and its effects on hydraulic conductance of human dentin. Furthermore, we assessed the physical durability of this sealing, as measured by its resistance to aggressive solutions and toothbrushing, and identified appropriate vehicles and delivery systems for its application. It was hypothesized that this novel material may potentially be used as a dental desensitizing agent.

2. Materials and methods

2.1. Materials

We synthesized bioactive glass (BAG), using a sol–gel method. The composition of this glass was 65 mol% SiO_2, 31 mol% CaO, and 4 mol% P_2O_5.

To maintain the highest homogeneity possible, all starting compounds were high-purity metal alkoxides. Tetraethyl orthosilicate (TEOS, $C_8H_{20}O_4Si$) was used as the precursor for silica (SiO_2) in the final glass; calcium methoxyethoxide (CMOE, $C_6H_{14}O_4Ca$) was the precursor for lime (CaO); and triethyl phosphate (TEP, $C_6H_{15}O_3PO$) was used to yield phosphate (P_2O_5). All of the alkoxide reagents were purchased commercially (Sigma–Aldrich). The methoxyethanol solution served as a mutual solvent for all of the alkoxides. The solutions were prepared in a dry nitrogen environment, and water vapor was introduced by aging them in a 100% humidity chamber at 37 °C. This served to initiate hydrolysis and glass formation. After mixing, the resulting glasses were cast into polyethylene containers and allowed to hydrolyze undisturbed for up to 3 weeks. They were aged in distilled water, air-dried and stabilized in a furnace at 600 °C, using a ramp and soak sequence over two days to completely remove residual alcohols and alkoxide components, while retaining high surface area through moderate–high porosity formation. After rapidly cooling, the glasses were coarsely crushed with mortar and pestle, and subsequently ball-milled with zirconia beads for 8 h in an ethanol solution. The resulting powders were dried at 37 °C and sieved to less than 35 μm. The particles underwent further processing in a micronizer (Sturtevant, Hanover MA), resulting in a distribution of particles with a size range from less than 1 μm to about 20 μm, as measured by laser diffraction (Malvern Mastersizer 2000, Malvern Instruments, Westborough, MA). The surface area of all powders was measured using the BET technique (Quantasorb, Quantachrome Corp., Syosset, NY).

Table 1 – The concentration of ionic species in SBF.

Ionic species	Concentration in SBF (mM)
Mg^{2+}	1.5
Ca^{2+}	2.5
K^+	5.0
Na^+	142.0
SO_4^{2-}	0.5
HPO_4^{2-}	1.0
HCO_3^-	4.2
Cl^-	147.8

In order to verify the bioactivity of these powders, samples (10 mg) were immersed in 5 ml of Simulated Body Fluid (SBF) for up to 14 days (see Table 1). Following immersion, the powders were rinsed, dried and examined using Fourier Transform Infrared Spectroscopy (FTIR).

2.2. Tooth preparation

Dentin/pulp chamber specimens ($n = 3$–5 for each treatment) were prepared from human teeth as shown in Fig. 1. In brief, intact human molars free from caries and restorations were sectioned perpendicular to the long axis of the tooth using a low-speed rotary saw and a diamond wafering blade. The initial cut was made apically and far enough below the dentin–enamel junction so as to leave a small amount of the original pulp chamber. The occlusal surface of the tooth was removed with a second cut parallel to the first and just superior to the pulp horns. This resulted in a thin cylinder of tooth with intact dentin on the surface of the sample. The prepared tooth was mounted on an acrylic block using cyanoacrylate adhesive (Zap-it; Dental Ventures of America) through which a 15 gauge stainless steel (SS) tube had been inserted to provide entry into the pulp chamber. The fresh dentin surface was ground using #600 SiC until perfusion of water through the dentin was visible with moderate pressure applied through the SS tube via a water-filled syringe. Care was taken to not perforate the thin dentin layer. The SS tube was used throughout the remainder of the experiments when the specimens were being aged to provide 20 cm pressure with SBF to replicate physiologic conditions.

Each tooth surface was lightly etched with 35% phosphoric acid (15 s) on a microbrush to remove the resulting smear layer and open the tubules. Following etching, the surface was rinsed for 10 s and blotted dry with tissue, and then hydraulic conductance measurements were made as detailed below.

2.3. Experimental design

All conductance measurements were made following a modified procedure described by Pashley et al. [8], using a FloDec

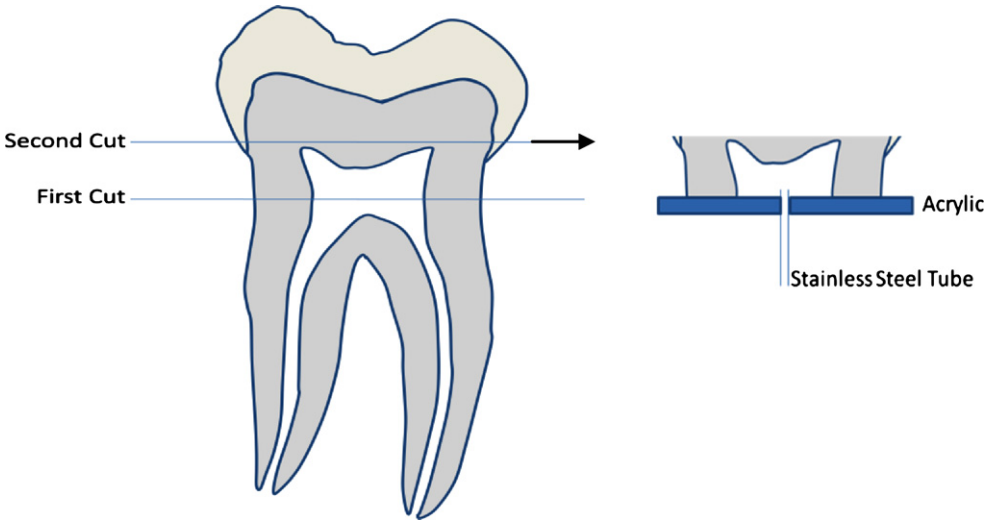

Fig. 1 – Location of cuts and resulting sample configuration.

Instrument (DeMarco Engineering, Switzerland) with SBF as the test fluid. In order to ensure a significant rate of conductance through the tubules, a relatively high pressure of 90 cm of SBF was maintained throughout the testing period. This pressure was achieved by arranging the SBF supply at a height of 90 cm above the dentin surface.

As an initial investigation, BAG powder, prepared as described above, was mixed for 60 s with 35% phosphoric acid gel (PA) as a carrier fluid. Samples were prepared as a 15 wt% mixture of the powder. The resulting slurry was immediately applied to the dentin surface and lightly brushed for 60 s ($n = 5$). As a non-bioactive control, we also prepared the slurry using a commercially available silica nanofiller as a thickening agent (OX50; 40 nm size; 50 m^2/g, OX-50; Degussa Inc., Germany) ($n = 3$). These particles, due to their small size, may penetrate and cause some occlusion of dentin tubules, but have no demonstrated ability to promote re-mineralization on dentin surfaces. These tests were conducted to ascertain whether any reduction in conductance was due to mere physical obturation of the tubules. Additional teeth samples were brushed with the carrier alone (without added particles) to observe the effect of PA on conductance ($n = 3$). Following the treatment, samples were rinsed with water and conductance measurements were made corresponding to 0, 1, 2, 96 and 168 h after treatment. Teeth were stored in sealed containers at 100% relative humidity at 25 °C under physiologic pressure (20 cm SBF) between tests. Data are reported as a percent reduction in fluid conductance.

Following these initial investigations, additional carrier fluids were selected for testing. This was necessitated by the fact that the bioactive glass began to gel in the phosphoric acid within minutes, thus providing inadequate stability. Thus, non-acidic, essentially non-toxic, and water soluble solutions were investigated. These were ethanol, propylene glycol (PPG), hydroxyethyl methacrylate (HEMA), and glycerol. Teeth were prepared as above, with conductance measurements being made after preparing the samples (with the smear layer), after etching the samples with PA to remove the smear layer and open the tubules, and after allowing the specimen to remain undisturbed in sealed containers at 100% relative humidity at 25 °C under physiologic pressure (20 cm SBF) for 1 h after etching. Following this 1-h period, the slurries were applied by microbrush for 60 s, rinsed with water and conductance measurements were again made at 1 h, 24 h, 4 days and 1 week after application ($n = 3$). Teeth were again stored in sealed containers at 100% relative humidity at 25 °C under physiologic pressure between measurements. The specimen treatment conditions are summarized in Table 2.

2.4. *Durability measurements*

To assess durability of the reduction in conductance, a group of specimens ($n = 5$) was treated with BAG in glycerol, and subsequently exposed to a series of toothbrush abrasion tests (see Fig. 2). Glycerol was selected for these investigations since it provided the highest reduction in conductance of the four solutions and was therefore deemed to be the most promising

Table 2 – Sample types and treatments.

Treatment	*n*	Fluid	Particles
Tx 1	5	Phosphoric acid gel	BAG
Tx 2	3	Phosphoric acid gel	OX-50
Tx 3	3	Phosphoric acid gel	None
Tx 4	3	Ethanol	BAG
Tx 5	1	Ethanol	None
Tx 6	3	Propylene glycol	BAG
Tx 7	1	Propylene glycol	None
Tx 8	3	HEMA	BAG
Tx 9	1	HEMA	None
Tx 10	3	Glycerol	BAG
Tx 11	1	Glycerol	None
Tx 12		Ethanol	OX-50
Tx 13		HEMA	OX-50
Tx 14		Propylene glycol	OX-50
Tx 15		Glycerol	OX-50

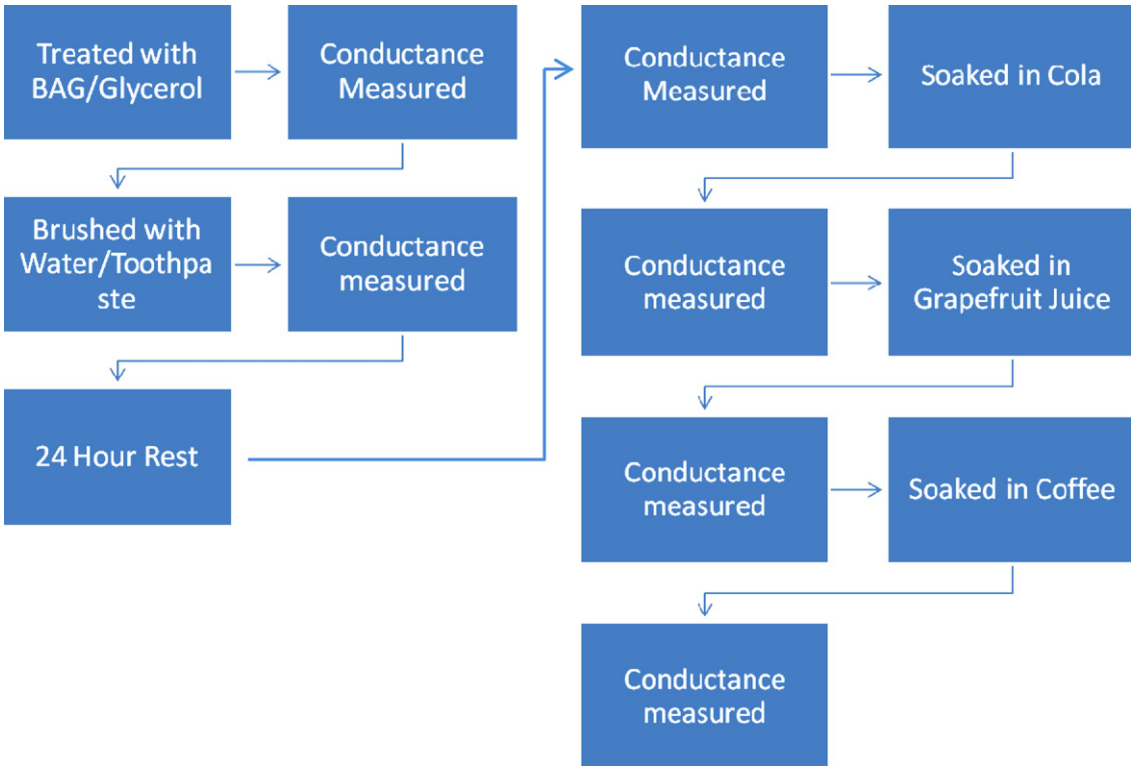

Fig. 2 – Sequence of brushing treatments used to assess durability.

carrier vehicle. The tooth was mounted on a rotating wheel attached to a DC gear motor and subjected to abrasion from a soft bristle toothbrush (Oral B #30, Iowa City, IA) while being rotated through water/toothpaste slurry containing 1 tube (181 g) of toothpaste in 500 ml water at 60 rpm for 5 min [15]. Fluid conductance testing was performed before and immediately after brushing (specimens were rinsed with copious water to remove the toothpaste and then blotted dry with tissue), as well as 24 h after toothbrushing (the sample was kept under physiologic pressure between events). Next, the toothpaste/water slurry was replaced sequentially with undiluted cola (pH = 2.5), undiluted grapefruit juice (pH = 3.1), and finally coffee (pH = 5.7), and the sample was cycled without brushing through these fluids for five minutes each. Conductance was again measured before and after each exposure. A set of control teeth which were etched but had nothing applied were also tested after each procedure ($n = 5$).

Scanning electron microscopy (SEM) (6400, JEOL Corp., Peabody, MA) was used to examine surfaces of the samples before and after treatment. These samples were dried and sputter-coated (Hummer VII, Anatech USA, Union City, CA) with approximately 10 nm of gold/palladium.

2.5. *Statistical analyses*

Statistical analyses were used to examine the change in % of original conductance measured. Comparisons between carriers over time were analyzed with 2-way ANOVA/Tukey's test ($p \leq 0.05$), while 1-way ANOVA/Tukey's test ($p \leq 0.05$) was used to compare the effects of BAG vs. OX-50 in the same carrier (phosphoric acid) and PA.

3. Results

The FT-IR results from immersing the original BAG particles in SBF showed the appearance of peaks indicative of new carbonate apatite formation on the soaked BAG, specifically the P–O stretch at 960 cm^{-1} and the P–O bend vibrations at 565 cm^{-1} and 598 cm^{-1} (Fig. 3) [16]. The presence of these new peaks is a necessary and sufficient condition to demonstrate bioactivity of the BAG starting materials [17,18].

All of the carriers were easy to mix with the BAG powder, and the particles remained fully suspended in the carrier for at least 5 min after mixing. They were all easy to disperse across the tooth surface. Of the carriers used in these experiments, ethanol required the most attention during application, as it was the only solution which quickly evaporated from the tooth surface, leaving it dry. Representative curves plotting changes in hydraulic conductance over time using additional carriers, showed that the glycerol was the most effective at reducing conductance (to less than 25% of the initial level) immediately, and at each time period (Fig. 5). To assess durability of the reduced conductance, the four carriers were compared at 7 days, and showed significantly lower and equivalent conductance for PPG and glycerol as compared with ethanol and HEMA (Fig. 6). The PPG showed a gradual reduction in conductance (to an ultimate reduction of around 30% of initial level). This behavior was distinguishable from the more immediate effect provided by the other carriers.

Results from the glycerol–BAG slurry durability experiment are shown in Fig. 7 as the percent conductance relative to

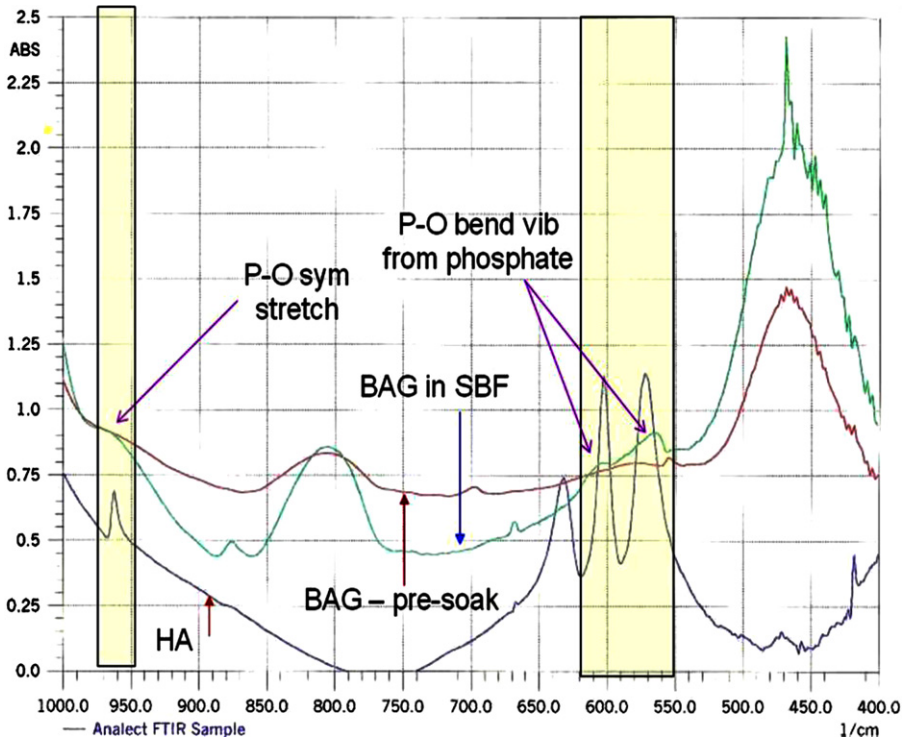

Fig. 3 – FT-IR patterns of BAG before and after soaking. Pure hydroxylapatite is shown for comparison. The presence of new peaks after soaking at 960 cm^{-1}, 565 cm^{-1} and 598 cm^{-1} confirmed that apatite formation occurred on these bioactive glass powders.

the original untreated surface. Samples which received this treatment had significant reduction in conductance at 24 h post-brushing with toothpaste, and even after being subjected to repeated soaking in acidic solutions. At each stage, the teeth treated with the BAG had significantly lower conductance than the untreated control, with the differences ranging from about 45 to 80% reduced conductance.

Scanning electron micrographs of untreated and treated teeth (Fig. 8) show the tubular occlusion produced by the BAG. Examination of the surfaces after exposure to brushing and acidic solutions showed the most pronounced tubular occlusion for the glycerol and PPG carriers.

4. Discussion

Bioactive glasses have been increasingly studied for their ability to aid in the regeneration and remineralization of tissues throughout the human body, including both orthopedic as well as dental tissues [19–21]. These materials are relatively inexpensive and are easy to synthesize. They spontaneously produce a carbonate apatite layer on their surface when immersed in physiologic fluids. This aspect of the material was demonstrated in this study using FTIR to show the formation of a carbonated apatite on the surface of the original BAG particles when soaked in SBF. This ability has led to speculation that they might be used to assist the body to self-heal dentin and enamel in vivo [20,22,23].

The processes of demineralization and re-mineralization are known to occur continuously within the oral cavity [24]. The intimate delivery of BAGs into a region undergoing demineralization might be able to push the balance more toward the deposition of mineral by the solubilization of calcium and phosphate. Likewise, if introduced into open tubules, BAG particles should be able to reduce hypersensitivity by occluding the tubules, but perhaps more importantly by inducing mineralization within and across the individual tubule itself, permanently sealing the fluid pathway.

The results presented in Fig. 4 demonstrate that all of the materials provided an immediate reduction in conductance with respect to the initial value for the teeth. The use of the OX-50 powder and the PA alone did not reduce the conductance to the same extent as the BAG-containing treatment.

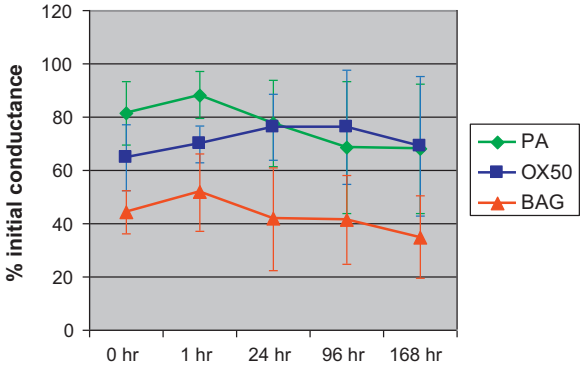

Fig. 4 – Percent reduction in hydraulic conductance following treatment with BAG and OX-50 particles.

These initial results for all of these materials are likely due to physical occlusion of the tubules after demineralization of the surface mineral and exposure of the collagen network, which can collapse over the surfaces of the tubules.

The BAG particles are of a suitable size range to effectively cover the tubules as well as be brushed into them. This may explain why these materials provided a greater decrease in conductance initially as compared with the etch alone or the etch with nanosized silica particles. The BAG powders, however, continued to further reduce conductance at the 96 and 168 h time points. This reduction likely corresponds to the chemical reaction occurring between the BAG particles and the SBF perfusing from the dentinal tubules and soaking the surface. The FTIR results confirm that apatite precipitation occurs with these glasses, and by the 96-h time point, this mineral phase is likely already beginning to deposit within tubules and subsequently block fluid movement. This continued reduction is not seen with the other treatments, where the initial blockage remains relatively constant. The OX-50 particles, although they may occlude the tubules initially, do not chemically bond with the dentin, and may simply be being washed away during rinsing or due to the pulpal pressure during storage.

Initial attempts to apply the BAG powder mixed with water directly to dentin surfaces did not create good coverage or adequate retention. When suspended in the PA carrier vehicle, both types of particle-containing slurries (OX-50 and BAG) had a suitable viscosity to be easily dispersed on the surface of the tooth samples, and were sufficiently viscous to be retained on the tooth. It was hypothesized that the PA would lightly etch the tooth surface and would carry the particles along with it. PA mixed with BAG did deliver the particles to the surface and provided statistically lower conductance measurements at all time points when compared to the PA alone or the PA with OX-50, the latter two demonstrating equivalent conductance change (Fig. 4). However, the PA containing BAG particles tended to become increasingly viscous over time and needed to be freshly prepared for each test. This led to our exploration of the alternative carriers.

The delivery of BAG particles with all of the subsequently selected carriers was highly effective in reducing hydraulic conductance through the dentinal tubules. Since all of the carriers were completely water soluble, wetting of the tooth surface with the mixtures was easily accomplished. All provided an immediate and sustained reduction.

As shown in Fig. 5, the glycerol–BAG slurry showed the greatest initial decrease in conductance, about a fourfold reduction at 7 days after only a single application of BAG. The glycerol carrier had a relatively high viscosity compared to the other carriers, especially the ethanol and HEMA. We suspect that this increased viscosity as well as the hygroscopic nature of this carrier may partly account for the carrier material staying in place on the tooth surface and delivering BAG particles to the open tubules and the surface better than the ethanol and HEMA carriers. Additionally, the glycerol carrier may have benefitted from more hydrogen bonding occurring with the dentin surface due to the three alcohol groups present as compared to two in PPG and only one in the ethanol and HEMA slurries. The greater reduction for the carriers containing BAG vs. the carrier alone (Fig. 6) provides evidence that the reduced conductance was not due to the carrier alone.

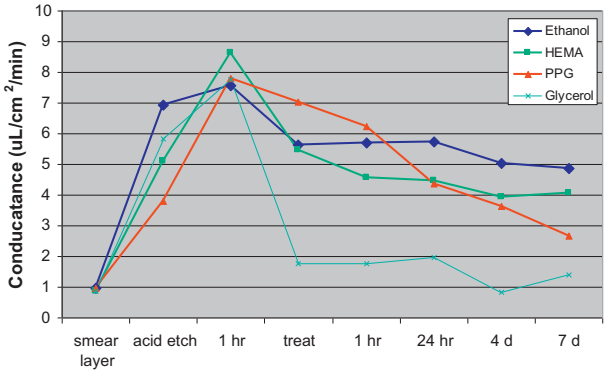

Fig. 5 – Representative curves of conductance vs. time comparing the four carriers.

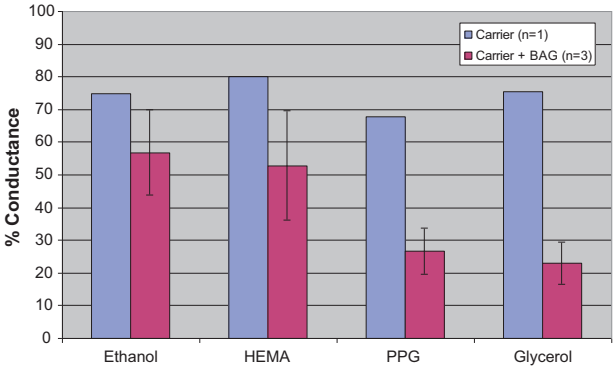

Fig. 6 – Comparison of the hydraulic conductance of the surfaces treated with the BAG in the four carriers after 7 days of storage under physiologic pressure.

The presence of a chemical bond between the BAG and dentin is further bolstered by the maintained reduction in conductance following brushing and immersion in various beverages, as compared to brushed control specimens. It was expected that the physical action of brushing and the chemical action of the acidic solutions would reduce the effectiveness

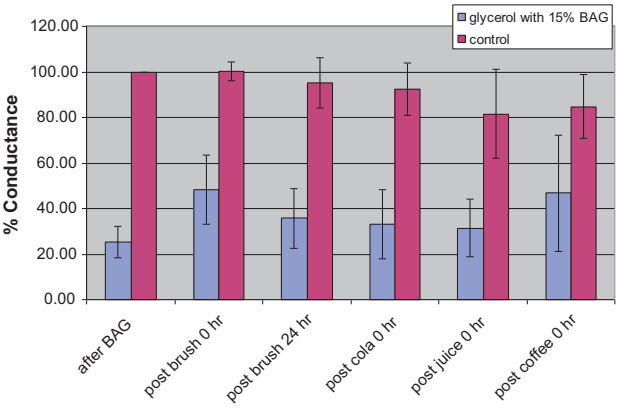

Fig. 7 – Hydraulic conductance measurements from durability test samples undergoing the brushing sequence shown in Fig. 2.

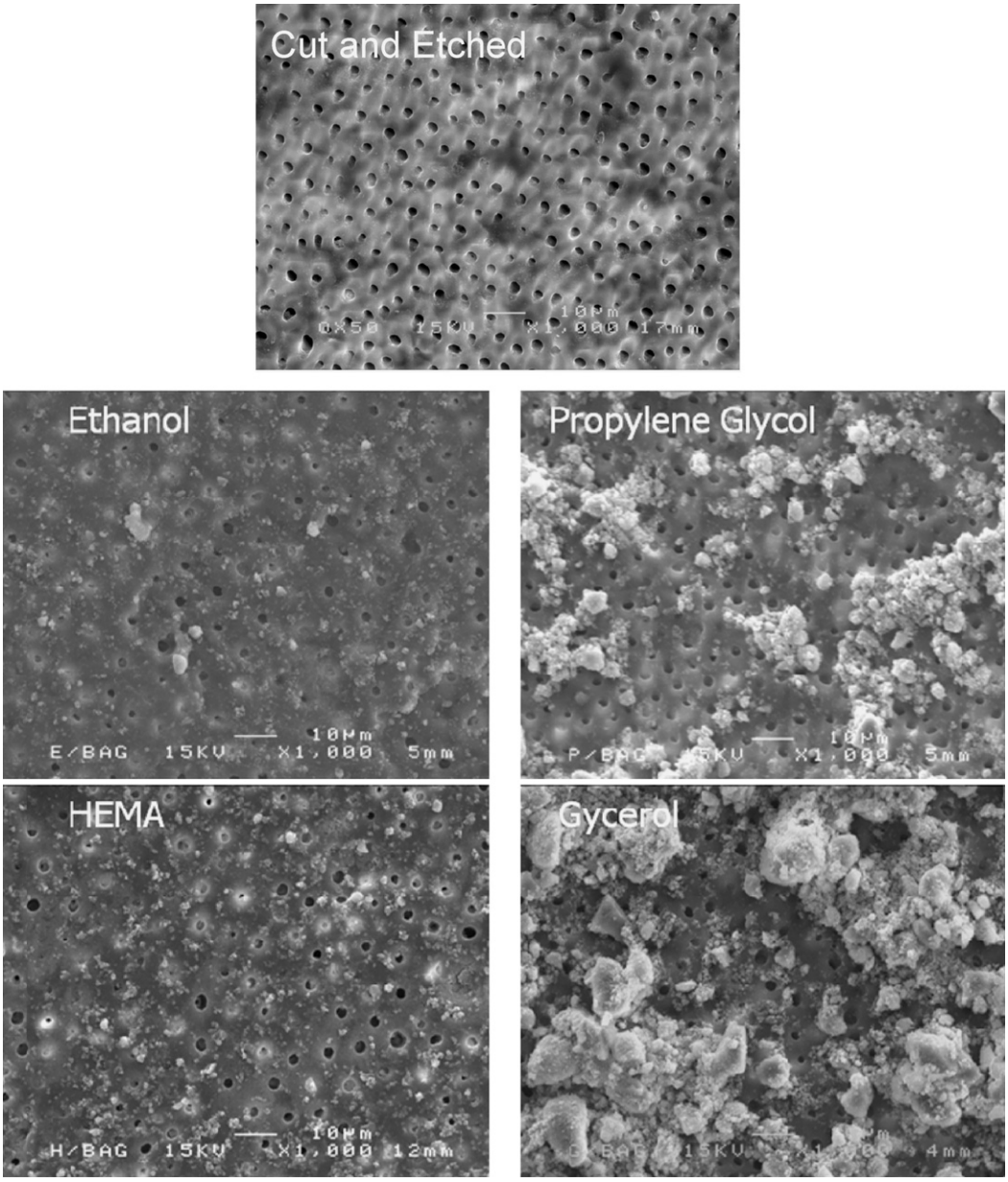

Fig. 8 – SEM micrographs of dentin surfaces. A, a sample surface immediately following etching; B–E, treated with BAG in one of the four carriers. B, ethanol; C, HEMA; D, PPG; E, glycerol.

of the treatment. However, as shown in Fig. 7, this did not occur.

Scanning electron microscopic analysis showed evidence of finely ground BAG particles covering the dentin surface and occluding tubules after treatment (Fig. 8). The fact that the BAG particles remained on the surface and within the exposed dentinal tubules after brushing with toothpaste and soaking in the three acidic solutions suggests that the layer is tenaciously attached to the dentin. It is very likely that the BAG particles have begun to chemically react and adhere to the dentin surfaces as soon as they come into contact with these surfaces and the fluids present within and upon them.

Gillam et al. [1] recently reported on the SEM appearance of tooth surfaces following treatment with Bioglass®. In contrast with our findings with our sol–gel formulated BAGs, they report that the Bioglass® particles are “easily displaced by handling and washing”. We propose that the difference in results has to do with the greatly increased surface area available for chemical reactivity obtained by the sol–gel synthesis method. The BAGs have surface areas which are orders of magnitude higher than commercially available melt-derived glasses [25]. This allows for rapid ion exchange and formation of the apatitic layer which aids in chemically bonding the glass to the dentin surface.

5. Conclusion

Application of the nano-structured sol–gel bioactive glass with the carrier fluids tested in the study showed a significant reduction in fluid conductance through dentin at each time period vs. the carrier alone. Furthermore, it was shown that the application of non-bioactive particles in a carrier did not further reduce the conductance beyond that obtained with the carrier alone. Application of the BAG mixed into a slurry with glycerol was effective at producing an immediate reduction in fluid conductance, and maintaining it for at least 7 days, even after brushing of the surface and repeated soaking in different acidic solutions, suggesting that the occluding layer provided by the BAG is tenaciously bound to the dentin surface.

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REFERENCES

[1] Gillam DG, Tang JY, Mordan NJ, Newman HN. The effects of a novel Bioglass dentifrice on dentine sensitivity: a scanning electron microscopy investigation. J Oral Rehabil 2002;29:305–13.
[2] Bartold PM. Dentinal hypersensitivity: a review. Aust Dent J 2006;3:212–8.
[3] von Troil B, Needleman I, Sanz M. A systematic review of the prevalence of root sensitivity following periodontal therapy. J Clin Periodontol 2002;29:173–7.
[4] Absi EG, Addy M, Adams D. Dentine hypersensitivity. A study of the patency of dentinal tubules in sensitive and non-sensitive cervical dentine. J Clin Periodontol 1987;14:280–4.
[5] Brännström M, Linden LA, Astrom A. The hydrodynamics of the dental tubule and of pulp fluid. A discussion of its significance in relation to dentinal sensitivity. Caries Res 1967;1:310–7.
[6] Jacobsen PL, Bruce G. Clinical dentin hypersensitivity: understanding the causes and prescribing a treatment. J Contemp Dent Pract 2001;15:1–12.
[7] Walters PA. Dentinal hypersensitivity: a review. J Contemp Dent Pract 2005;15:107–17.
[8] Pashley DH, Matthews WG, Zhang Y, Johnson M. Fluid shifts across human dentine in vitro in response to hydrodynamic stimuli. Arch Oral Biol 1996;41:1065–72.
[9] Hench LL, Paschall HA. Direct chemical bond of bioactive glass-ceramic materials to bone and muscle. J Biomed Mater Res 1973;7:25–42.
[10] Neo M, Nakamura T, Ohtsuki C, Kokubo T, Yamamuro T. Apatite formation on three kinds of bioactive material at an early stage in vivo: a comparative study by transmission electron microscopy. J Biomed Mater Res 1993;27:999–1006.
[11] Ducheyne P, Qiu Q. Bioactive ceramics: the effect of surface reactivity on bone formation and bone cell function. Biomaterials 1999;20:2287–303.
[12] Vallet-Regí M, Rámila A, Padilla S, Muñoz B. Bioactive glasses as accelerators of apatite bioactivity. J Biomed Mater Res A 2003;66:580–5.
[13] Gatti AM, Simonetti LA, Monari E, Guidi S, Greenspan D. Bone augmentation with bioactive glass in three cases of dental implant placement. J Biomater Appl 2006;20: 325–39.
[14] Mitchell JC. Aging of bioactive glass bone grafting materials. In: Eliades, et al., editors. Dental materials in vivo. Chicago, IL: Quintessence; 2003. p. 263–76.
[15] da Costa J, Adams-Belusko A, Riley K, Ferracane JL. The effect of various dentifrices on surface roughness and gloss of resin composites. J Dent 2010 March 1 [Epub ahead of print].
[16] Fowler BO. Infrared studies of apatites. I. Vibrational assignments for calcium, strontium, and barium hydroxylapatites using isotopic substitution. Inorganic Chem 1974;13:194–207.
[17] Hench LL. Bioceramics: from concept to clinic. J Am Ceram Soc 1991;74:1487–510.
[18] Kokubo T, Kushitani H, Sakka S, Kitsugi T, Yamamuro T. Solutions able to reproduce in vivo surface-structure changes in bioactive glass-ceramic A–W. J Biomed Mater Res 1990;24:721–34.
[19] Lin CP, Lin FH, Tseng YC, Kok SH, Lan WH, Liao JD. Treatment of tooth fracture by medium energy CO_2 laser and DP-bioactive glass paste: compositional, structural, and phase changes of DP-Bioglass paste after irradiation by CO_2 laser. Biomaterials 2000;21:637–43.
[20] Efflandt SE, Magne P, Douglas WH, Francis LF. Interaction between bioactive glasses and human dentin. J Mater Sci Mater Med 2002;13:557–65.
[21] Forsback AP, Areva S, Salonen JI. Mineralization of dentin induced by treatment with bioactive glass S53P4 in vitro. Acta Odontol Scand 2004;62:14–20.
[22] Waltimo T, Mohn D, Paqué F, Brunner TJ, Stark WJ, Imfeld T, et al. Fine-tuning of bioactive glass for root canal disinfection. J Dent Res 2009;88:235–8.
[23] Jefferies SR, Pameijer CH, Appleby D, Boston D, Lööf J, Glantz PO. One year clinical performance and post-operative sensitivity of a bioactive dental luting cement—a prospective clinical study. Swed Dent J 2009;33:193–9.
[24] Featherstone JD. Dental caries: a dynamic disease process. Aust Dent J 2008;53:286–91.
[25] Mitchell JC. A bioactive glass material for the delivery of Bone Morphogenetic Proteins: synthesis by the solution sol–gel method, physical and chemical analyses, and in-vitro testing. Thesis, The Ohio State University, 1999 OCLC# 43272687; 1999.