Interaction between bioactive glasses and human dentin

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This study explores the interaction between bioactive glasses and dentin from extracted human teeth in simulated oral conditions. Bioactive glasses in the Na_2O–CaO–P_2O_5–SiO_2 and MgO–CaO–P_2O_5–SiO_2 systems were prepared as polished disks. Teeth were prepared by grinding to expose dentin and etching with phosphoric acid. A layer of saliva was placed between the two, and the pair was secured with an elastic band and immersed in saliva at 37 °C for 5, 21 or 42 days. The bioactive glasses adhered to dentin, while controls showed no such interaction. A continuous interface between the bioactive glass and dentin was imaged using cryogenic-scanning electron microscopy (SEM). However, after alcohol dehydration and critical point drying, fracture occurred due to stresses from dentin shrinkage. SEM investigations showed a microstructurally different material at the fractured interface. Chemical analyses revealed that ions from the glass penetrated into the dentin and that the surface of the glass in contact with the dentin was modified. Microdiffractometry showed the presence of apatite at the interface. Bonding appears to be due to an affinity of collagen for the glass surface and chemical interaction between the dentin and glass, leading to apatite formation at the interface.

1. Introduction

Bonding dental restorations to dentin is challenging due to dentin's intricate, water-containing structure. Dentin is a mineralized collagen-based tissue containing roughly 70 wt % apatite, 20 % collagen, and 10 % water; the most prominent structural features of dentin are the dentinal tubules which run perpendicularly from pulp to enamel [1]. To prepare dentin for bonding, the collagen network of dentin is exposed by etching to allow penetration of the adhesive [2, 3]. Unfortunately, duplication of the etching method used for enamel does not give the same good results because of structural differences between dentin and enamel, and the hydrophobicity of the adhesive and the hydrophilicity of the dentin substrate. Recent formulations of dentin adhesives rely on the combination of hydrophilic monomers and a bonding resin; however, optimization of this technique is still required in specific situations, such as the bonding of ceramic pieces [4, 5]. Additionally, contraction upon curing and composite thermal expansion mismatch with dentin make the separation of the restoration from the dental tissue possible, leading to microleakage and subsequent decay [6, 7]. To overcome these challenges, many efforts are underway toward creating new dental materials and adhesives. One possible route is to create a more interactive dental material through the incorporation of bioactive glasses.

Bioactive glasses and glass–ceramics are used for a variety of hard tissue replacement and repair applications. In addition to being biocompatible [8], bioactive glasses bond to and stimulate the regeneration of bone [9–12]. These materials are used in prosthetic devices, such as bone and dental implants, where bonding is a key to success. Other applications include bone cement, and bone and periodontal fillers where regeneration of the bony tissue is the objective. Bioactive glasses and glass–ceramics form a layer of carbonated apatite on their surfaces *in vivo* and create a contiguous bond to bone [13, 14]. The bioactive material, when placed in a biological environment such as body fluid, chemically interacts with the environment and the natural tissues in contact with the material. Generally, this interaction

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involves chemical modification of the glass and release of ions into the surrounding biological environment, which is already supersaturated with respect to the constituents of apatite. A layer of apatite forms on the surface of the bioactive material and participates in the bond to bone [15]. Thus far, the use of bioactive glass in dentistry has been limited mainly to implantology [16–21] and periodontology [22–25].

Several components involved in the body environment and the oral environment are similar which motivates this study of the interaction between bioactive glasses and dentin. Saliva has a comparable ionic composition to plasma [1], and bone and dentin are analogous in composition, if not in microstructure [26]. Additionally, bone and dentin have similarities in their processes for formation; a main difference is that dentin is not vascularized [1, 27].

This report focuses on the interaction of bioactive glasses with dentin from extracted human teeth and is a detailed follow-up to a preliminary investigation [28]. Experiments in this study are designed to uncover the phenomena that occur at the glass–dentin interface in a simulated oral environment. As such, the most convenient set-up to analyze the interface is chosen: a polished bulk piece of glass pressed onto a prepared dentin surface in the presence of saliva. While the experiments and methods are not designed to test particular concepts in using bioactive glass as an adhesive or in a restoration, they do provide results of interest to the practical challenges that exist in restorative dentistry.

2. Experimental procedure

2.1. Specimen preparation

Two compositions of glass were investigated: $24.5Na_2O–24.5CaO–6P_2O_5–45SiO_2$ wt % (45S5) and $4.6MgO–44.9CaO–16.3P_2O_5–34.2SiO_2$ wt % (AW). Glass powders were used as-received from Specialty Glass, Inc. (Oldsmar, FL) to form glass beads. 45S5 is a common bioactive glass [13], and AW glass can be crystallized into an apatite-wollastonite glass–ceramic [14]. The beads were prepared by melting the powders separately in a platinum crucible at 1500 °C for 1 h, and quenching the molten glass onto an aluminum block. Annealing the beads for 4 h at 650 °C reduced internal stresses. Two AW glass beads were crystallized at 950 °C for 4 h; all others were left as amorphous. The bioactive materials were polished with 120, 240, and 400 grit silicon-carbide paper to provide a flat surface for experimentation.

Study of the interaction required the preparation of bioactive glass–dentin pairs. The glasses investigated were 45S5 glass (9 samples) and AW glass (14 samples). For comparison, pairs with AW glass–ceramic (2 samples) were also studied. Other materials used in the experiments were human dentin, whole and artificial saliva, and phosphoric acid. Whole saliva was collected a few hours before experiments were started. The artificial saliva used in this study, based on a recipe from the Dental School at the University of Alabama, Birmingham [29], was prepared in a 1000 ml batch; the batch was stirred continuously for at least 24 h prior to the start of each experiment. Human extracted third molars were polished interdentally to expose hydrated dentin surfaces and then etched with 35 % phosphoric acid for 15 s. The orientation of the dentinal tubules relative to the surface varied. To create a glass–dentin pair, a layer of saliva was placed between the flat surfaces of dentin and glass, and the two were then secured together with an elastic band and immersed in whole or artificial saliva. Each pair was placed in a separate plastic container with 40 ml of saliva, and the sealed containers were then placed in an incubator at 37 °C for 5, 21, or 42 days.

Several control pairs were prepared in the same manner as previously described except that one of the three key components was replaced with an inert substitute. Three microscope glass slide–dentin pairs were incubated in saliva; here, a nonbioactive glass replaces the bioactive glass. Two bioactive glass–alumina pairs were incubated in saliva to investigate the effect of replacing dentin with an inert substrate. Lastly, two bioactive glass–dentin pairs were incubated in water instead of saliva. All controls were incubated for either 21 or 42 days.

Additionally, polished disks of the two types of bioactive glass as well as the bioactive glass–ceramic were placed in artificial saliva without dentin to investigate growth of apatite on the exposed surfaces. The polished samples were placed in a small plastic box with 8 ml of saliva, sealed with parafilm and incubated at 37 °C. After 5, 21, and 42 days, the glasses were removed from the saliva and evaluated with optical microscopy and X-ray diffraction analysis.

The plastic containers (holding the pairs) were taken from the incubator after either 5, 21, or 42 days. The pairs were removed from the liquid and the elastic band cut. All pairs containing a bioactive glass stayed adhered even with some handling (see Table I), while others separated immediately (see Table II). All of the adhered pairs were kept hydrated until further specimen preparation steps could be carried out.

Two of the bioactive glass–dentin pairs in saliva for 21 days (one with 45S5 glass and one with AW glass) were allowed to dry in ambient conditions before further analyses. For these specimens, shrinkage of dentin resulted in stresses that caused the pairs to fracture at their interfaces. Study of these materials was limited to the surfaces that were in contact before drying.

All other adhered pairs were prepared for examination

TABLE I Summary of specimens which adhered

Pair	Saliva type	No. of samples	Incubation time (days)
45S5 glass/dentin	Artificial	1	5
45S5 glass/dentin	Whole	1	21
45S5 glass/dentin	Artificial	1	21
45S5 glass/dentin	Whole	2	42
45S5 glass/dentin	Artificial	2	42
AW glass/dentin	Artificial	1	5
AW glass/dentin	Whole	5	21
AW glass/dentin	Artificial	2	21
AW glass/dentin	Whole	2	42
AW glass/dentin	Artificial	2	42

TABLE II Summary of specimens which did not adhere

Pair	Liquid	No. of samples	Incubation time (days)
AW glass-ceramic/dentin	Whole saliva	2	42
Glass slide/dentin	Whole saliva	1	21
Glass slide/dentin	Artificial saliva	1	21
Glass slide/dentin	Artificial saliva	1	42
AW glass/alumina	Artificial saliva	1	21
45S5 glass/alumina	Artificial saliva	1	21
AW glass/dentin	Water	1	21
45S5 glass/dentin	Water	1	21

by embedding it in a PL-1 liquid plastic resin (Photoelastic Division Measurements Group, Inc., Raleigh, NC). This two-component room-temperature-curing system was used to stabilize the interface for analyzes without introducing elevated temperatures. The embedded samples were then cut longitudinally to the interface in 1 mm increments using a slow speed diamond saw. Slices were then dehydrated by immersing in 50%, 70%, and 80% ethanol baths for 10 min each and 95% and 100% ethanol baths for 20 min each; samples were then directly transferred to a Tousimis Advanced Manual Critical Point Dryer – model 780A for the final drying step. These specimens will be referred to as CPD slices.

2.2. Microstructure studies

Two scanning electron microscopy (SEM) techniques were carried out on the slices to reveal interfacial structure. Hydrated slices were imaged at low temperatures with cryogenic-SEM (cryo-SEM) using a JEOL : JSM 840. The slices were prepared by freezing in liquid nitrogen for several minutes to preserve the microstructure. The frozen slices were coated with 50 Å of Pt and raised to a temperature of $-110\,^{\circ}C$ for sublimation of any ice crystals. During imaging, the sample stage was maintained at a temperature of $-180\,^{\circ}C$ using liquid nitrogen. Critically point dried (CPD) slices were mounted perpendicular to their interfaces (to observe their cross-sections), coated with a thin gold layer and imaged using a Hitachi S-800 FE-SEM. Additionally, optical microscopy and FE-SEM were performed on the exposed surfaces of the ambiently dried samples and the bioactive glasses which had been soaked in saliva (without dentin).

2.3. Chemical analysis

Both ambiently dried pairs that separated and CPD slices were investigated by electron microprobe analysis (EMPA) using a JEOL Electron Probe X-ray Microanalyzer – model 8900R. The dentin and bioactive glass from the ambiently dried pairs were mounted with the interfacial side up and were coated with carbon. Analysis was performed using 10 kV electrons resulting in a maximum analysis depth of 2 μm. Cross-sections of the embedded specimens were polished before critical point drying with 45, 30, 6, and 3 μm diamond media to provide a smooth surface for analysis. Once dried, the slices were mounted perpendicular to the interface and coated with a thin carbon coating before analysis as above.

2.4. Microdiffractometry

X-ray diffraction analyses were carried out using a Bruker-AXS Microdiffractometer with a 2.2 kW sealed Cu X-ray source. All samples were mounted to a glass holder using double-sided tape. Our previous study showed data with unidentified peaks which were traced to a clay mounting material [28]. The new mounting method here avoids this interference. The bioactive glasses and glass–ceramic that were soaked in artificial saliva (without dentin) were examined using a 0.8 mm^2 area size with incident X-rays normal to the sample. Similarly, after manual separation of the CPD slices, microdiffractometry was carried out on glass surfaces that had been in contact with dentin in the pair. Samples of dentin were also analyzed under the same conditions for comparison.

The dentin and the glass from the ambiently dried pairs were evaluated using microdiffraction. Distinct areas on the glass and dentin surfaces could be defined: the area where the two materials were in contact before drying and the periphery. To analyze the areas that were in contact, a smaller 0.5 mm^2 area was used with a glancing angle of $\Omega = 1^{\circ}$. The glancing angle allowed analysis of the surface region only.

3. Results

3.1. Qualitative assessment

After a 5, 21 or 42 day period, the pairs were removed from the incubator and interaction was qualitatively assessed (see Tables I and II). The 21 and 42 day bioactive glass–dentin pairs (total of 17 samples, see Table I) all remained intact after removal of the elastic band and handling while the five day pairs (two samples) were only weakly held together and came apart easily. This assessment of interaction did not allow any quantitative comparisons between the different bioactive glass–dentin pairs, but it was certain that all bioactive glasses adhered to dentin and that this adherence was strengthened with time. Also, adherence was observed for both whole and artificial saliva. The two bioactive glass–dentin pairs that were allowed to dry in ambient separated on handling after 24 h of drying. Evidence of the interaction was observed visually as the outline of the bioactive glass was apparent on the dentin and vice-versa. In contrast to the bioactive glasses, the bioactive glass–ceramic did not adhere to dentin, falling apart immediately after the elastic band was removed.

The control pairs in which bioactive glass was replaced with a glass slide immediately separated upon removal of the elastic band (see Table II). Additionally, controls with an inert alumina substrate replacing dentin or water replacing saliva did not show any interaction. These qualitative observations clearly show that all three components: bioactive glass, dentin, and saliva are necessary for adherence. While statistical methods were not employed to analyze this data, it is apparent, that there is a significant difference between the control group and the bioactive group.

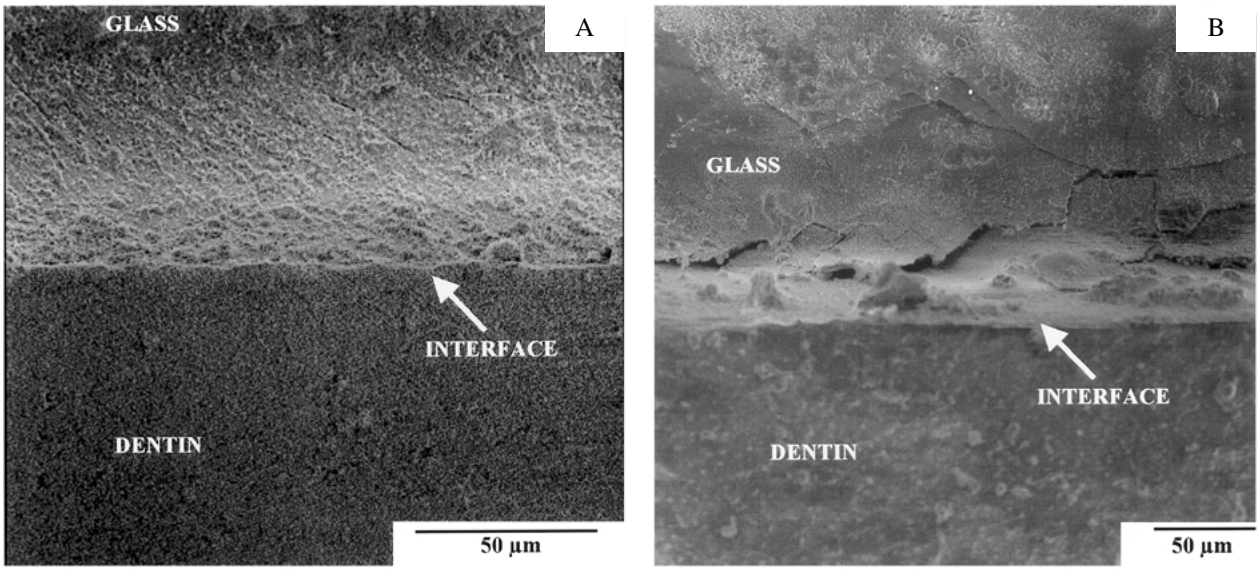

Figure 1 Cryogenic-SEM images of frozen cross-section slices of (A) 45S5/dentin, and (B) AW/dentin pairs after soaking in artificial saliva for 42 days.

3.2. Microstructure studies

Fig. 1 shows cryo-SEM images of the hydrated glass–dentin pairs. These images confirm that bioactive glass and dentin are in intimate contact before dehydration. Slicing may have resulted in some micro-fracturing of the glass in one of the specimens. In contrast, dried slices imaged in FE-SEM show separation of the dentin from the glass (see Fig. 2) as CPD techniques failed to prevent shrinkage-induced fracture. In these images, a material with a different microstructure appears at the interface between dentin and glass, and the fracture follows a jagged path. In situations where fracture occurred in the glass near to the interface, a layer of adhered material on the dentin was apparent and vice-versa. No dramatic differences were noted between the glass types, as incubation time varied from 21 to 42 days or as whole and artificial saliva were used.

Optical microscopy of the bioactive glasses (with no dentin present) after 5, 21, and 42 days in saliva reveal the evolution of a layer on the exposed surfaces. This new layer was shown to be apatite by X-ray diffraction (see below). Samples soaked for five days have a new layer completely covering their surfaces; surfaces of samples after 21 days of soaking appear to have a denser layer, and after 42 days, the layer is much thicker and more developed. No layer was apparent on the bioactive glass–ceramic.

Optical microscopy was also performed on the dentin and bioactive glass from the pairs separated by ambient drying. An outline of where the bioactive glass was adhered to the dentin was evident and vice-versa is apparent (see Fig. 3). SEM of the dentin surface (see Fig. 4) revealed that the dentinal tubules were not visible except for a small region in the center of the pair which had apparently not made good contact to the dentin. This result indicates that the fracture left some new material behind on the dentin surface or that the dentin surface had been modified. Interestingly, the polished and etched

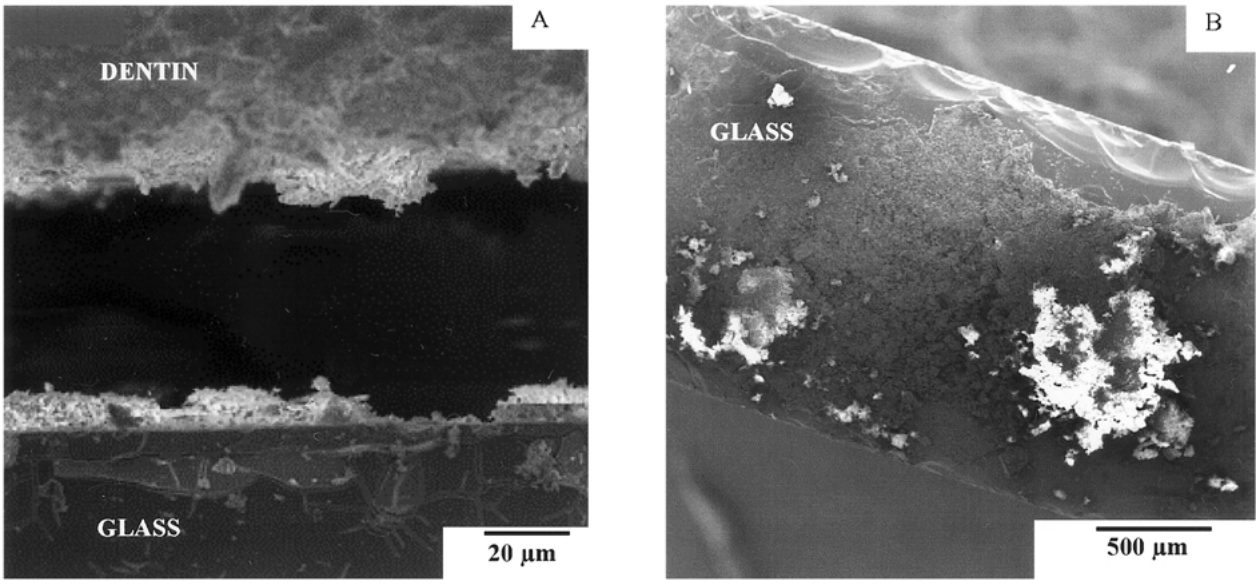

Figure 2 Images of CPD-dried glass–dentin pairs after a three-week incubation period in whole saliva: (A) SEM of cross-section slice, and (B) AW glass surface which was in contact with dentin; adhered material was analyzed by microdiffractometry.

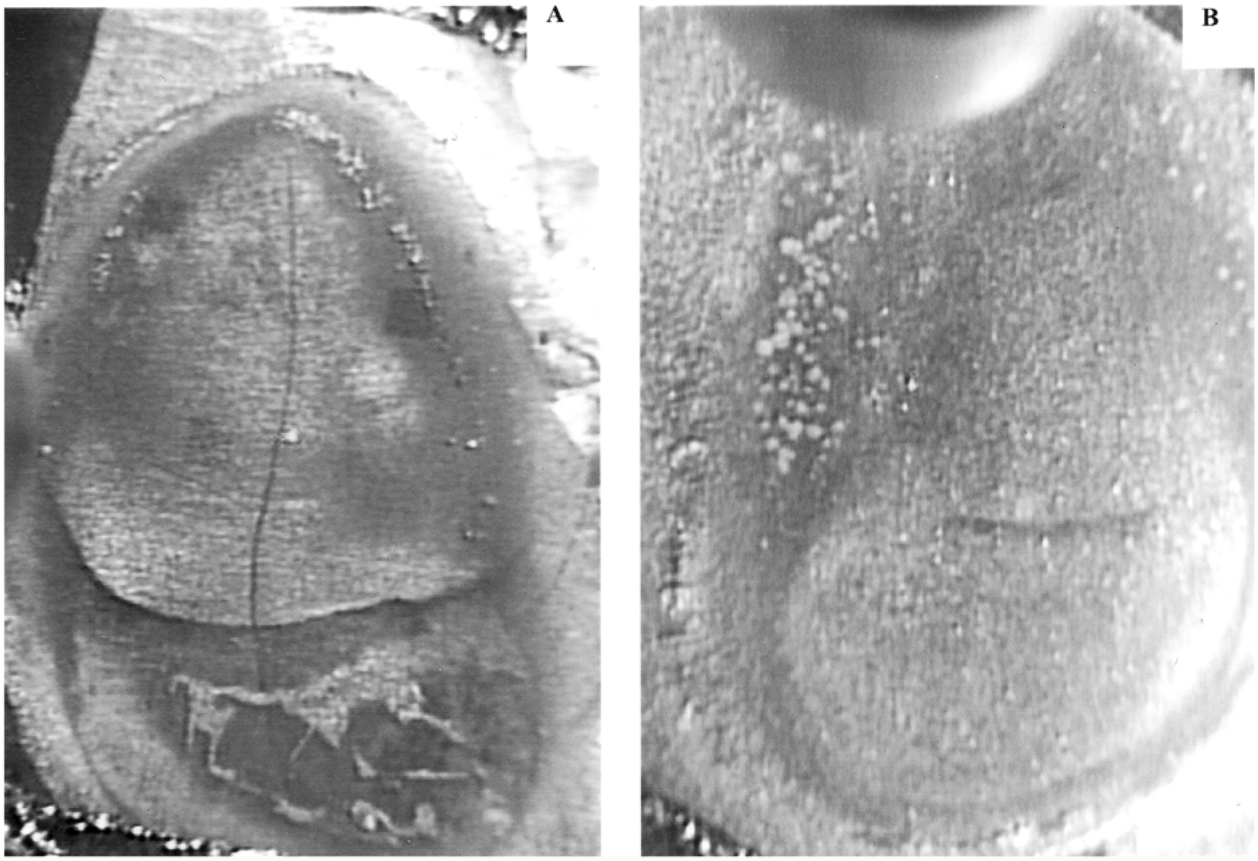

Figure 3 Images (14X) of a 45S5 glass–dentin pair separated due to ambient drying: (A) dentin, and (B) 45S5 glass. The two surfaces were opposing one another during incubation.

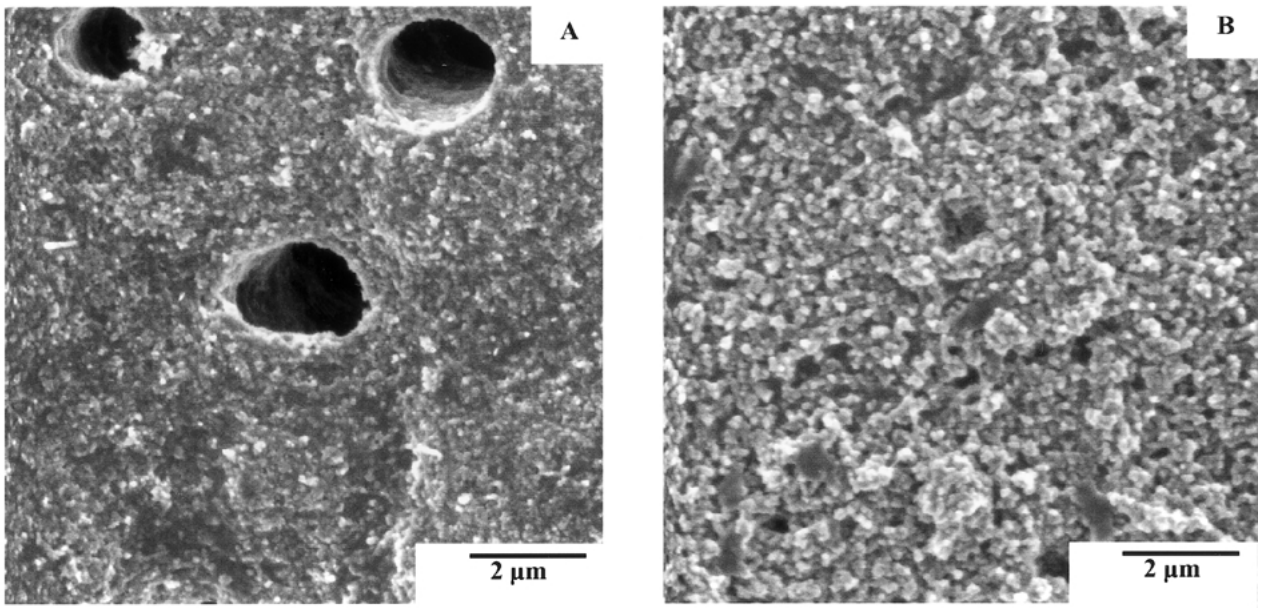

Figure 4 SEM of dentin that was in contact with 45S5 glass, after separation due to ambient drying: (A) small region near the center where contact with 45S5 glass was not good; tubules are visible, and (B) a more common area that was in good contact with 45S5 glass; tubules are not visible.

dentin that was in contact with the saliva alone (no glass) also showed a lack of tubule structure, presumably due to interaction with the saliva.

3.3. Chemical analysis

Elemental maps for each side of the ambiently dried pairs were collected for Si, Ca, and P using EMPA. The results are summarized here without display of the color maps. On the dentin surface that was in contact with the bioactive glass, maps showed the presence of Ca, P, and Si. Maps collected in areas of the dentin that were not in contact with the glass (only exposed to saliva) showed higher Ca and P levels, but no Si. Analyses performed on the glass surface that was in contact with the dentin showed the presence of Ca/P-rich, Si-poor areas. Areas not in contact with the dentin could not be analyzed due to surface curvature. These results demonstrate the

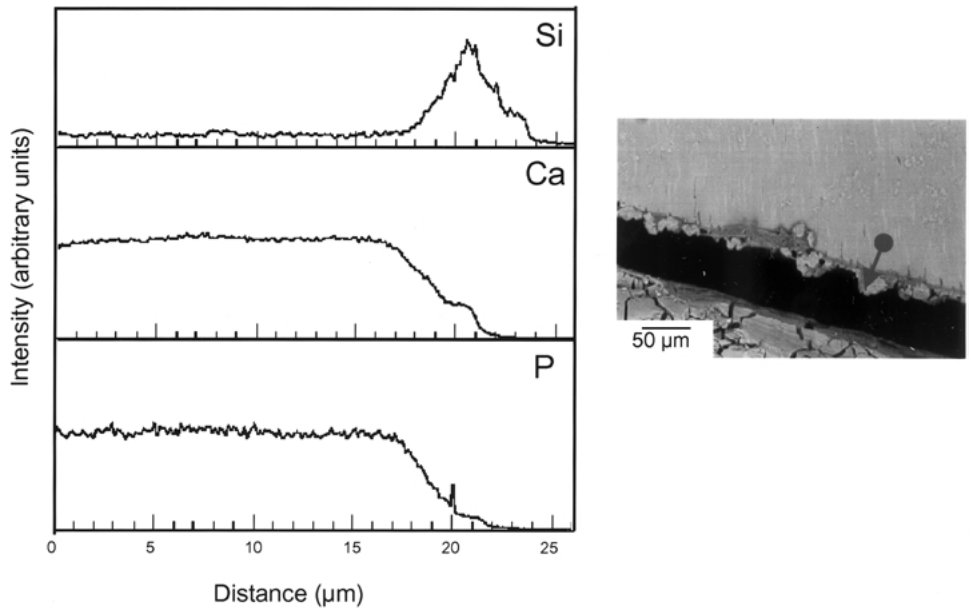

Figure 5 Electron microprobe scan data and corresponding SEM for a 45S5/dentin pair after a three-week incubation in whole saliva, followed by slicing and critical point drying. The line scan path from dentin to the interface is denoted by the arrow. Analysis was carried out on the dentin side of the pair (glass side is still visible in view) after drying-induced fracture. Scales for Ca, P, and Si concentration are relative and not comparable quantitatively.

chemical interaction between the dentin and bioactive glass.

Compositional profiles of the CPD pairs were obtained for Si, Ca, and P using EMPA (see Figs 5 and 6). Line scans were run from the dentin side of the pair up to the fracture surface. Dramatic changes are evident as the fracture surface is approached. Far from the fracture surface, uniform Ca and P compositions are observed. But, approximately 5–8 μm from the fracture surface, the concentrations of Ca and P decrease with a corresponding increase in Si concentration. These changes occur roughly at the point where adhered interfacial materials were observed in the SEM images. Based on the high Si content, this material likely contains glass with a modified composition due to interaction with saliva. The data in Fig. 6 show that the ions released from the glass penetrate deeply into dentin and may concentrate in the dentinal tubules. Additionally, these results show that the demineralized zone, which was present after etching (roughly 5–7 μm, [3]), was not present.

3.4. Microdiffractometry

Microdiffractometry data collected for bioactive glass surfaces exposed to saliva (with no dentin present) showed several peaks matching hydroxyapatite (JCPDS09-0432) for glasses soaked for 21 and 42 days

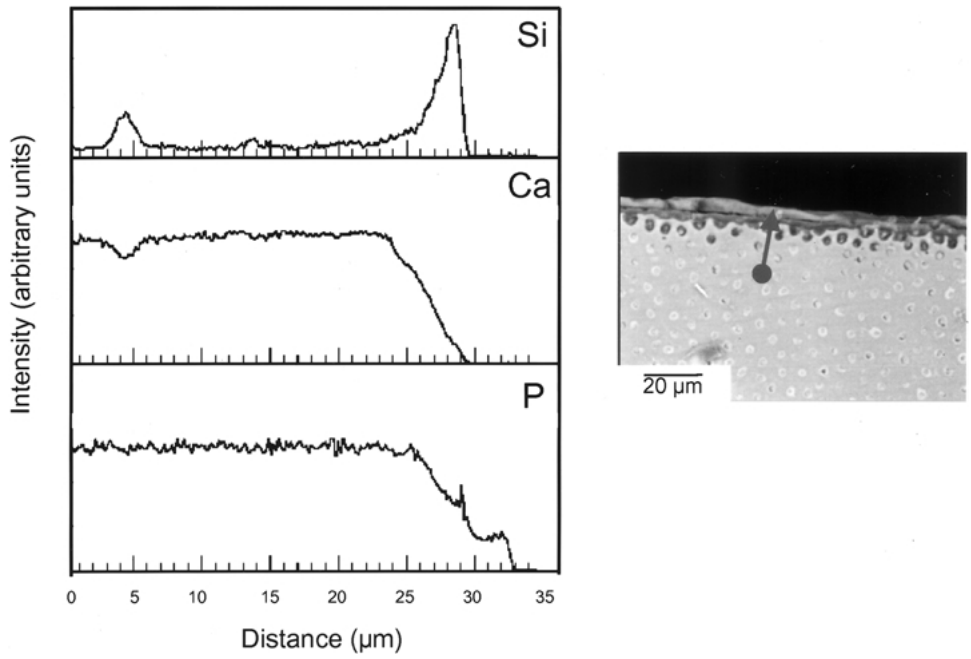

Figure 6 Electron microprobe scan data and corresponding SEM for an AW/dentin pair after a three-week incubation in whole saliva, followed by slicing and critical point drying. The line scan path from dentin to the interface is denoted by the arrow. Analysis was carried out on the dentin side of the pair (glass side is not visible in view) after drying-induced fracture. Scales for Ca, P, and Si concentration are relative and not comparable quantitatively.

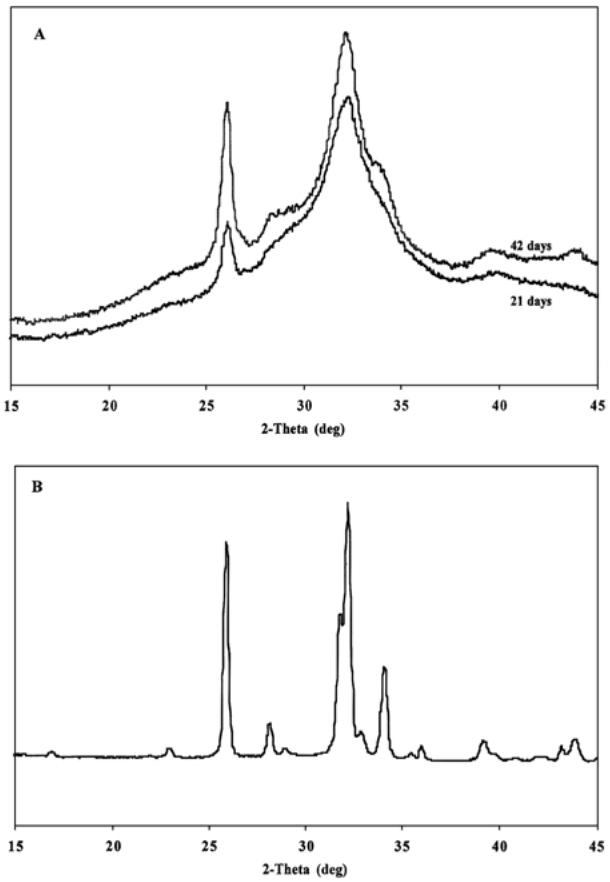

Figure 7 Microdiffraction data for 45S5 glass immersed in artificial saliva for (A) 21 days and 42 days with no dentin. Similar data were obtained for AW glass immersed in artificial saliva. (B) Microdiffraction data from human dentin shown for comparison. Data is shown in arbitrary intensity.

(see Fig. 7). For both the AW and 45S5 glass samples, these peaks increased in intensity as the glass was soaked for longer times. The diffraction pattern for apatite formed on the glass surface is different from that obtained from dentin using the same microdiffraction technique. By contrast with the bioactive glasses, the AW glass–ceramic soaked in saliva showed no development of a surface apatite after 42 days.

Microdiffractometry was carried out on dentin and bioactive glass, which separated due to ambient drying. As discussed previously, the dentin surface that was in contact with the bioactive glass had evidence of a different structure in areas where glass had been adhered. These areas were analyzed using glancing angle microdiffractometry. Apatite was observed on both of the dentin surfaces (see Fig. 8). The glancing angle technique analyzed the very near surface structure which was shown above to have altered microstructure and chemistry compared to the bulk of the dentin. Further, the crystallinity and features of the diffraction pattern were different than that characteristic of natural dentin, especially for the dentin in contact with the 45S5 glass. These factors indicate that apatite at the surface of the dentin is likely due to interaction with saliva and the glass. The opposing 45S5 and AW glass surfaces that were in contact with the dentin did not show evidence of crystalline apatite (although their surfaces had Ca/P-rich regions, as discussed above).

Bioactive glass surfaces that were in contact with dentin, but separated after CPD were also analyzed. These glass samples showed a more prominent adhered material on their surfaces (see Fig. 2) as compared with the specimens that were dried in ambient, likely due to the different nature of the drying induced fracture. Diffraction patterns confirm the presence of apatite in the adhered material for both AW and 45S5 glass surfaces (see Fig. 9). Apatite was not found in the diffraction data taken from areas with no prominent adhered material. The apatite shown in Fig. 9, like that grown on bioactive glass in saliva, has a different diffraction pattern than natural dentin.

4. Discussion

Bioactive glasses interact with dentin from extracted human teeth after soaking in saliva at body temperature.

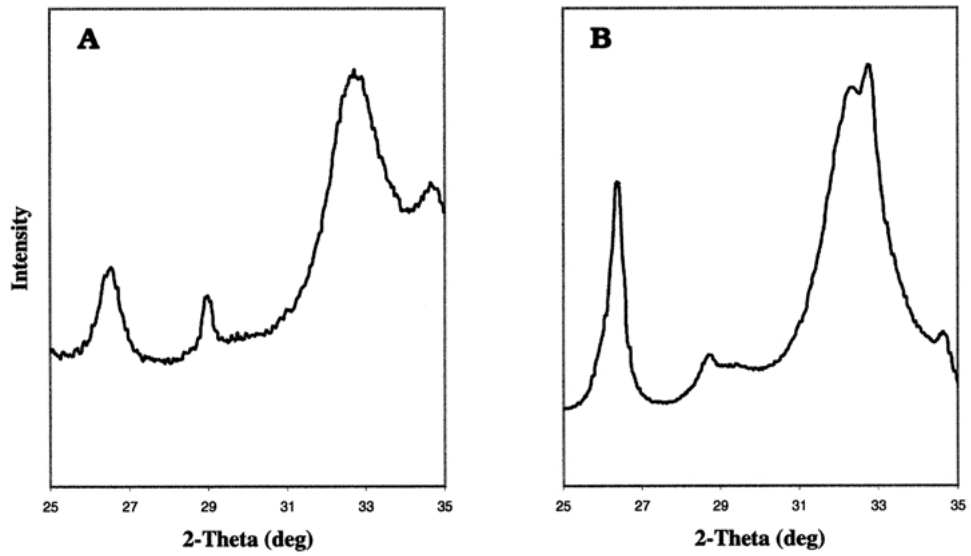

Figure 8 Glancing angle microdiffraction data for dentin surfaces that were in contact with (A) 45S5 glass, and (B) AW glass for a three-week period in artificial saliva, and then separated due to ambient drying. Data was taken from the surface of the dentin in areas where obvious interaction with bioactive glass had occurred. Results show apatite peaks (JCPDS09-0432) for both surfaces of dentin.

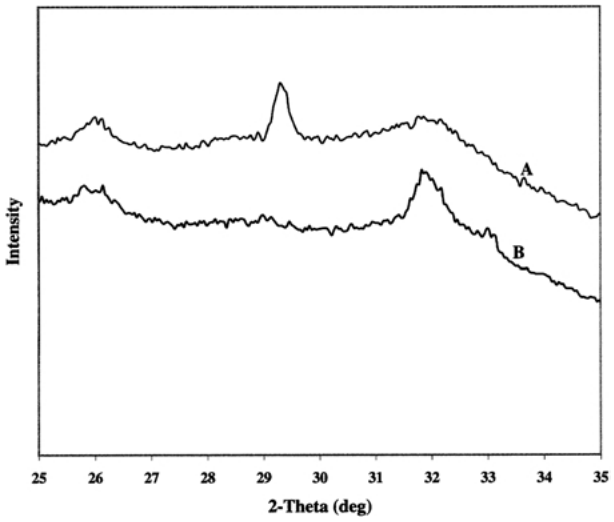

Figure 9 Microdiffraction data for a (A) 45S5 glass surface, and (B) AW glass surface which were in contact with dentin for a 42 day incubation period in whole saliva. Apatite peaks are evident (JCPDS09-0432).

All of the bioactive glass–dentin pairs incubated in saliva remained intact after removal of the elastic band. The interaction between bioactive glass and dentin was observed after five days. The pairs remained intact after removal of the elastic band but separated with handling. All the pairs after 21 and 42 days remained intact during handling and sample preparation for cryo-SEM, showing that this longer incubation period allows for a stronger interaction to develop. Interestingly, the bioactive glass–ceramic, which is known to be less interactive in the body than the glass form [30], did not adhere to dentin. Non-bioactive glass–dentin pairs also fell apart as did the experimental set-ups with alumina replacing the dentin and water replacing the saliva. These comparisons indicate that the chemical properties of the bioactive glass, as well as the presence of saliva, play a role in the interaction. Also of note is the fact that bacteria did not inhibit the adherence of bioactive glasses to dentin. The interfacial area created by the pair could have been an ideal place for bacteria to invade and prevent the interaction, but this interruption was not observed. The antibacterial effect of bioactive glasses has been noted in previous research [31] and is a desirable quality for dental applications.

The strong affinity and attachment between collagen fibrils and bioactive glass is one source for the observed bioactive glass–dentin interaction. When the pairs were prepared, the surface of the dentin was first etched to expose an open collagen network and then placed in contact with a polished piece of glass. Studies of the interfaces between bioactive glasses and soft and hard tissues [32, 33] show that the interdigitation of collagen with the modified surface of the bioactive glass is an important bonding mechanism. A similar attachment of the collagen fibrils from the dentin to the modified glass surface would allow the two pieces to remain intact after incubation in saliva. The continuous interface seen with cryo-SEM as well as the observed interaction at five days are likely due, at least in part, to the attachment of collagen to the bioactive glass.

The formation of an interfacial apatite is also a source of interaction. Bioactive glasses form apatite layers on their surfaces when implanted and *in vitro* when soaked in simulated body fluid [13, 34]. Similarly, results presented here show the formation of apatite on the surface of 45S5 and AW glasses on immersion in artificial saliva. Comparable results were noted for glass surfaces on incubation in whole saliva. The strengthening of the interaction between dentin and bioactive glass with time (i.e. 21 and 42 days) may be linked to apatite formation that occurs on the same time scale. The importance of apatite growth on the glass to the interaction is demonstrated by the direct correlation between a glass's ability to grow apatite in saliva and its ability to adhere to dentin. For example, the microscope slides and the bioactive glass–ceramic did not form apatite on their surfaces when soaked in saliva and also did not adhere to dentin, whereas all of the bioactive glass specimens did both.

Chemical analysis (EMPA) results show the chemical interaction between the bioactive glasses and dentin. Ions from the glass were found in the dentin and the surfaces of the glass that were in contact with dentin were modified. The ion exchange and release from bioactive glasses has been studied in simulated body environments [35, 36]. In these situations, the composition of the fluid changes as well as the surface chemistry of the glass [37, 38], leading to the formation of apatite on the glass surfaces. Similar changes are expected here in a simulated oral environment, except that ion release from the glass is directed into the dentin. These ions will increase the level of super saturation with respect to apatite. Saliva, a necessary component in the adherence, also provides calcium and phosphate ions. Under these conditions, apatite can be expected to form at the interface on the glass surface and in the demineralized zone created by etching. The demineralized zone, in particular, is an ideal site for apatite growth [39].

Microdiffractometry of the dentin surface that was separated from the glass after ambient drying showed the presence of apatite. The origin of this apatite and that found adhered to the glass surfaces after critical point drying is difficult to trace due to the irregular nature of the fractures at the interface. However, the studies of apatite formation in saliva, comparisons with the controls and natural dentin, and evidence for chemical interaction discussed above all point to the formation of apatite at the interface (in the demineralized zone of the dentin and/or on the glass surface). Such apatite formation may create mechanical interlocking between the glass and dentin, which strengthens adherence.

The bioactive glass–dentin interaction has exciting possibilities. Developing new materials and techniques to better adhere restorative materials to dentin is of great importance. While using bioactive glasses in their bulk form is not necessarily a viable option, the presence of bioactive glass may be of benefit to interfaces in new dental adhesives or tissue-engineered restorations. For example, leakage at the interface between microfilled composite fillings and dentin remains a problem that a new generation of dental materials capable of *in vivo* mineralization could remedy.

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