Evaluation of Pulp Response to Novel Bioactive Glass Pulp Capping Materials

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Abstract

Introduction: This study aimed to investigate dental pulp responses to novel bioactive glass (BG) pulp capping materials after direct pulp capping *in vivo*. **Methods:** Novel BG pulp capping materials are composed of powder and fluid. The powder is BG (82.36% SiO_2, 15.36% CaO, and 2.28% P_2O_5), and the fluid is provided in 2 kinds: (1) phosphate buffer solution (BG-PB) and (2) phosphate buffer solution with the addition of 1 wt% sodium alginate (BG-PB-SA). After mixing the powder and fluid, BG-PB and BG-PB-SA were prepared. Cavities with mechanical pulp exposure were prepared on maxillary first molars of Wistar rats. The exposures were randomly capped with BG-PB, BG-PB-SA, or mineral trioxide aggregate (MTA). After 1 (n = 6) and 4 weeks (n = 8), maxillary segments were obtained and prepared for histologic analysis with a scoring system. Statistical analysis was performed using the Kruskal-Wallis and Mann-Whitney U tests with the significance set at .05. **Results:** After 1 week, few inflammatory cells were present in the BG-PB, BG-PB-SA, and MTA groups. Moreover, a thin layer of newly generated matrix was observed in most specimens. After 4 weeks, all specimens from the 3 groups formed a heavy dentin bridge. BG-PB and BG-PB-SA groups exhibited no or slight inflammatory response, whereas the MTA group exhibited a slight to moderate inflammatory response. No significant difference was observed in pulp inflammation and dentin formation among the 3 groups at either time point (P > .05). **Conclusions:** When used as a pulp capping agent, BG-PB and BG-PB-SA had similar favorable cellular and inflammatory pulp responses to those of MTA. Therefore, BG is a promising pulp capping material. *(J Endod 2017;43:1647–1650)*

Key Words

Bioactive glass pulp capping material, direct pulp capping, mineral trioxide aggregate

Significance

A pulp capping agent can influence the success rate of direct pulp capping. We proposed promising bioactive glass pulp capping materials that showed similar favorable results with MTA when capped in a rat model.

Pulp capping materials are important in the success rate of direct pulp capping (1–3). An ideal pulp capping material should exhibit good sealing ability, good biocompatibility, strong antibacterial activity, and easy handling.

Calcium hydroxide (CH) is a conventional pulp capping material. However, it is a bioinert material, and it forms an incomplete dentin bridge with tunnel defects (4, 5). Mineral trioxide aggregate (MTA) is a bioactive material that has been recently applied in direct pulp capping. More homogenous (fewer tunnel defects) dentin bridges would form with MTA capping than with CH (4). MTA also obtained a higher clinical success rate than CH (1–3). Nevertheless, MTA still presents limitations, such as a long setting time, difficult handling characteristics, and cytotoxicity during the initial setting phase (6). Recently, several calcium silicate–based bioceramic materials, such as iRoot BP Plus (Innovative Bioceramix, Vancouver, Canada) and Biodentin (Septodont, St Maur des Fossés, France), have been reported to exert similar effects with MTA in pulp capping (4, 7–9), but clinical studies are lacking.

Bioactive glass (BG) is mainly composed of CaO, SiO_2, and Na_2O. Given that BG possesses a noncrystalline structure, it should exhibit better bioactivity than that of other bioceramics with a crystalline structure, such as MTA and iRoot BP Plus. BG presents good antibacterial properties (10) and induces proliferation, differentiation, and mineralization of human dental pulp cells (11, 12). Moreover, BG induces dentinlike tissue formation when transplanted with pulp tissue in the dorsum of nude mice (12). On the basis of the excellent BG properties, novel BG pulp capping materials were synthesized. The present study aimed to investigate pulp inflammation and dentin formation after direct pulp capping with novel BG pulp capping materials *in vivo*.

Materials and Methods

Preparation of Materials

BG pulp capping materials are composed of powder and fluid. The powder is BG (82.36% SiO_2, 15.36% CaO, and 2.28% P_2O_5) synthesized by using the sol-gel method combined with template technology. Two kinds of fluid are provided:

1. Only phosphate buffer solution (BG-PB)
2. Phosphate buffer solution with the addition of 1 wt% sodium alginate (BG-PB-SA)

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BG-PB and BG-PB-SA were obtained after mixing powder and fluid on a glass slab at a powder-to-liquid ratio of 1.4∼1.5 g/mL. BG pulp capping materials are easy to handle. The initial and final setting times were 5 to 7 minutes and 9 to 12 minutes, respectively. These materials were synthesized by the National Engineering Research Center for Tissue Restoration and Reconstruction of South China University of Technology, Guangzhou, China. ProRoot MTA (Dentsply Tulsa Dental, Tulsa, OK) was mixed with distilled water in accordance with the manufacturer's instructions.

Animals

This study was approved by the Ethics Commission of Peking University Health Science Center, Beijing, China. A total of 46 maxillary first molars from 23 male Wistar rats (180–200 g) were used for this *in vivo* study. Two time points were designed for observing pulp responses. Four teeth were used as negative controls, and 2 were used for each time point. Eighteen and 24 teeth were used for 1 week and 4 weeks, respectively. Each left and right first maxillary molar was capped using different materials.

Direct Pulp Capping Procedure

After being anesthetized with an intraperitoneal injection of 2% pentobarbital, the rats' teeth were cleaned and disinfected with cotton soaked in 75% ethanol. With the aid of a dental microscope (10.4–17.0× magnification) (OMS2350; Zumax Medical Co, Ltd, Suzhou, China), cavities were prepared on the mesial surfaces of the maxillary first molar using a sterilized ultrasonic tip (CAP 3; Satelec, Merignac, France). To avoid pulp impairment from heat, the teeth and cutting instruments were irrigated with sterile distilled water. Pulp was exposed using the tip of a #15 sterile stainless steel file through the remaining thin dentin of each cavity. Bleeding was controlled by pressing sterile paper points for a few seconds. The pulp exposure sites in the 3 experimental groups were directly capped with BG-PB, BG-PB-SA, or MTA. In the negative control group, the pulp was not capped with any pulp capping agent. All cavities were subsequently restored with glass ionomer cement (Fuji IX; GC International Corp, Tokyo, Japan) according to the manufacturer's instructions. The cusp tips of the opposing teeth were cut to minimize occlusal forces.

Sample Preparation and Histologic Analysis

The animals were anesthetized and sacrificed at 1 and 4 weeks after surgery. The maxillary sections, together with molars, were dissected and fixed in 4% paraformaldehyde for 24 hours at 4°C. The tissues were demineralized in 10% EDTA/phosphate-buffered saline solution and embedded in paraffin. The 5 μm-thick serial sections were cut in the mesiodistal direction. The slices were numbered, and the median sections were selected for hematoxylin-eosin staining.

Two observers were trained to evaluate the histologic features according to the criteria presented in Table 1 (9, 13, 14). The criteria of quality of dentin formation in the bridge were used to assess those of 4-week specimens only. Formal assessments were started when the 2 observers obtained 95% consistency. All specimens were rearranged and numbered. When disagreement existed between the 2 observers, they discussed it until a consensus was reached.

Statistical Analysis

The histologic evaluation results were analyzed statistically using the Kruskal-Wallis and Mann-Whitney *U* tests, with the level of significance set at .05.

Results

Pulp Inflammatory Response

At week 1, a moderate inflammatory response was observed in the negative control group (Fig. 1*A* and *E*). The BG-PB, BG-PB-SA, and MTA groups showed similar inflammatory cell responses (Table 2). Most of the specimens in the 3 groups exhibited no or few inflammatory cells (Fig. 1*B–D* and *F–H*). The remaining specimens showed mild inflammatory responses. No significant difference in the inflammatory responses was observed among the 3 groups ($P > .05$).

At week 4, necrosis was observed in the negative control group (Fig. 2*A* and *E*). All specimens in the BG-PB group exhibited no or few inflammatory cells (Fig. 2*B*, *F*, and *I*). In the BG-PB-SA group, 2 specimens showed mild inflammatory responses, and 6 specimens showed no or few inflammatory cells (Fig. 2*C*, *G*, and *J*). In the MTA group, 2 specimens exhibited moderate inflammation, 2 specimens showed mild inflammatory responses, and 4 specimens showed no inflammatory response (Fig. 2*D*, *H*, and *K*). No significant difference in the inflammatory responses was observed among the 3 groups ($P > .05$).

Hard Tissue Formation

At week 1, no hard tissue formed in the negative control group (Fig. 1*A* and *E*). In the BG-PB-SA and MTA groups, a slight layer of newly generated matrix next to the material was observed in 5 of 6 specimens (Fig. 1*C*, *D*, *G*, and *H*). Only half of the BG-PB group specimens exhibited mild hard tissue deposition (Fig. 1*B* and *F*). No significant difference was observed in hard tissue formation among the 3 groups ($P > .05$).

At week 4, an incomplete dentin bridge was observed in the negative control group (Fig. 2*A* and *E*). All specimens in the 3 experimental groups showed heavy hard tissue formation. Nearly all specimens presented irregular or regular tubular patterns in the newly formed calcified bridge except for 2 MTA group samples (no tubules present). The BG-PB, BG-PB-SA, and MTA groups formed well-organized tubular dentin bridges in 6, 4, and 2 samples, respectively (Fig. 2*B–D* and *F–H*). No significant difference existed in dentin bridge quality among the 3 groups ($P > .05$). The evaluation scores of each group after direct pulp capping are presented in Table 2.

TABLE 1. Criteria Used for the Histologic Analysis of the Pulps Treated with Direct Pulp Capping

Grade	Hard tissue formation	Inflammatory cell response	Quality of dentin formation in the bridge
1	Heavy: hard tissue deposition as complete and continuous dentin bridge	Absent or few inflammatory cells	Regular pattern of tubules
2	Moderate: hard tissue formation as incomplete and discontinuous dentin bridge	Mild: inflammatory cells only next to dentin bridge or area of pulp exposition	Irregular pattern of tubules
3	Slight: a layer of scattered and foggy hard tissue deposition	Moderate: inflammatory cells are observed in the part of coronal pulp	No tubules present
4	No hard tissue deposition	Severe: all coronal pulp	—

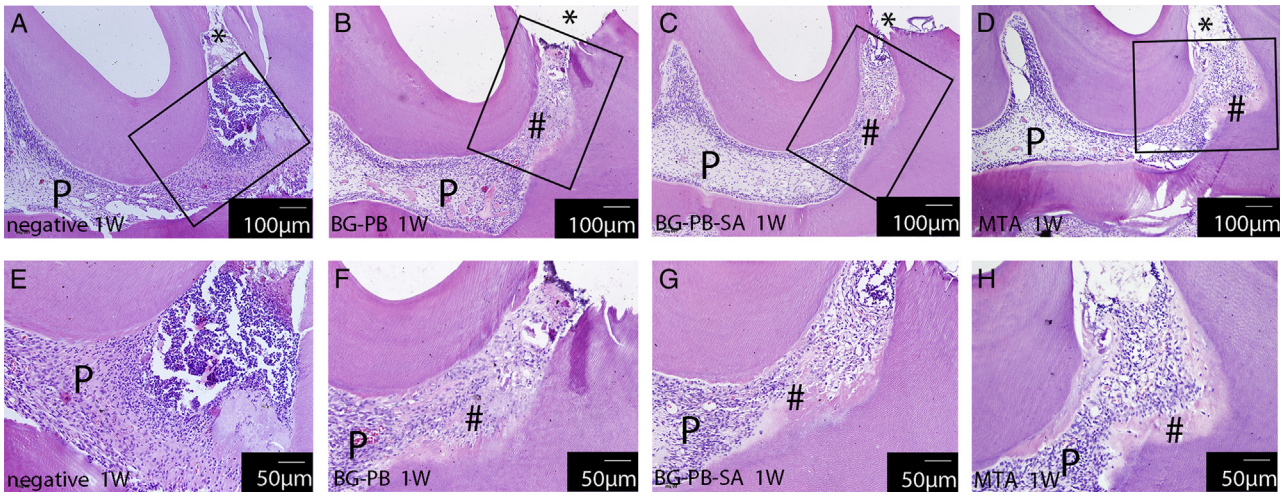

Figure 1. Hematoxylin-eosin staining evaluation of the effects of the (*A*) negative control, (*B*) BG-PB, (*C*) BG-PB-SA, and (*D*) MTA groups on direct pulp capping assay at 1 week. *E–H* present a high-magnification view of the area demarcated by the black rectangles in *A–D*. P, pulp; #, slight layer of hard tissue; *, pulp exposure.

Discussion

This study confirmed that the newly developed BG pulp capping materials can induce reparative dentin bridge formation at the injury sites of rat pulps. Research performed on rat molar teeth is reproducible in humans (15). However, given the small size of rat molar teeth, surgery is technologically difficult to operate. Hence, the present surgery was undertaken with the aid of a dental microscope (10.4–17.0× magnification). CH is the conventional primary standard for direct pulp capping materials. Nevertheless, recent studies proved that MTA induces more homogenous (fewer tunnel defects) and thicker (4, 16) dentin bridges and obtains a higher success rate than that of CH (1–3). Therefore, MTA was used as a positive control material in this study.

Studies have investigated the effects of BG on pulp capping. In 1 study, after 90 days of capping with 45S5 Bioglass powder (University of Florida Health Science Center, Jacksonville, FL), a layer of reparative dentin without tubules forms in all specimens (17). In another study, S53P4 BG (Abmin Technologies Ltd, Turku, Finland) mixed with saline was tested as a pulpotomy agent, and results showed that BG causes moderate to severe inflammatory responses at 2 weeks. Nevertheless, the pulp first shows a healing period and subsequently exhibits regular histology with vessel dilation at 4 weeks (18). These 2 studies both used traditional melt-derived BG powders in pulp capping, but the materials presented distinct shortages. When BG powder comes in direct contact with pulp tissue, a high local pH environment would form because of ion exchange. Such an alkaline environment is toxic to pulp cells. In addition, melt-derived BG displays low porosity, a smooth texture, and a small surface area, which result in lower bioactivity than that of sol-gel–derived BG (11, 19).

With technological development, the sol-gel method combined with template technology can solve agglomeration problems and control the size, texture, and morphology of BG. The BG used in our study, which served as the active substance for inducing pulp repairing, was synthesized by this new technology. Moreover, regular spherical BG exhibits better physicochemical and biological properties than that of irregular BG (20). Furthermore, phosphate buffer solution can serve as the initiator.

We observed the effects of BG pulp capping materials on direct pulp capping by preparing mechanical pulp exposures on rat molars. At week 1, BG-PB and BG-PB-SA groups exhibited results similar to those of the MTA group. The inflammatory response was localized, and a slight matrix layer was observed in most samples (Fig. 1*F–H*). At week 4, the BG-PB and BG-PB-SA groups induced a heavy layer of dentin bridge with regular or irregular tubules. Histologic analysis results showed that the outermost portion of the reparative dentin showed a low mineralization degree with some cell inclusions, whereas the deep layer presented highly mineralized tubular dentin without tunnel defects and cell inclusion. In some specimens, an osteoid dentin layer with a lacunar structure (Fig. 2*F* and *G*) was observed between these 2 layers.

TABLE 2. Grading of the Histologic Sections of the Pulps Subjected to Direct Pulp

		Inflammatory cell response score*					Hard tissue formation score*					Quality of dentin formation in the bridge score*			
Observation period	No. of specimens	1	2	3	4	Mean	1	2	3	4	Mean	1	2	3	Mean
1 week															
BG-PB	6	5	1	0	0	1.17	0	0	3	3	3.5	—	—	—	—
BG-PB-SA	6	4	2	0	0	1.33	0	0	5	1	3.17	—	—	—	—
MTA	6	5	1	0	0	1.17	0	0	5	1	3.17	—	—	—	—
4 weeks															
BG-PB	8	8	0	0	0	1	8	0	0	0	1	6	2	0	1.25
BG-PB-SA	8	6	2	0	0	1.25	8	0	0	0	1	4	4	0	1.5
MTA	8	4	2	2	0	1.75	8	0	0	0	1	2	4	2	2

BG-PB, bioactive glass with only phosphate buffer solution; BG-PB-SA, bioactive glass with the addition of 1 wt% sodium alginate; MTA, mineral trioxide aggregate.

*The criteria for scoring are shown in Table 1.

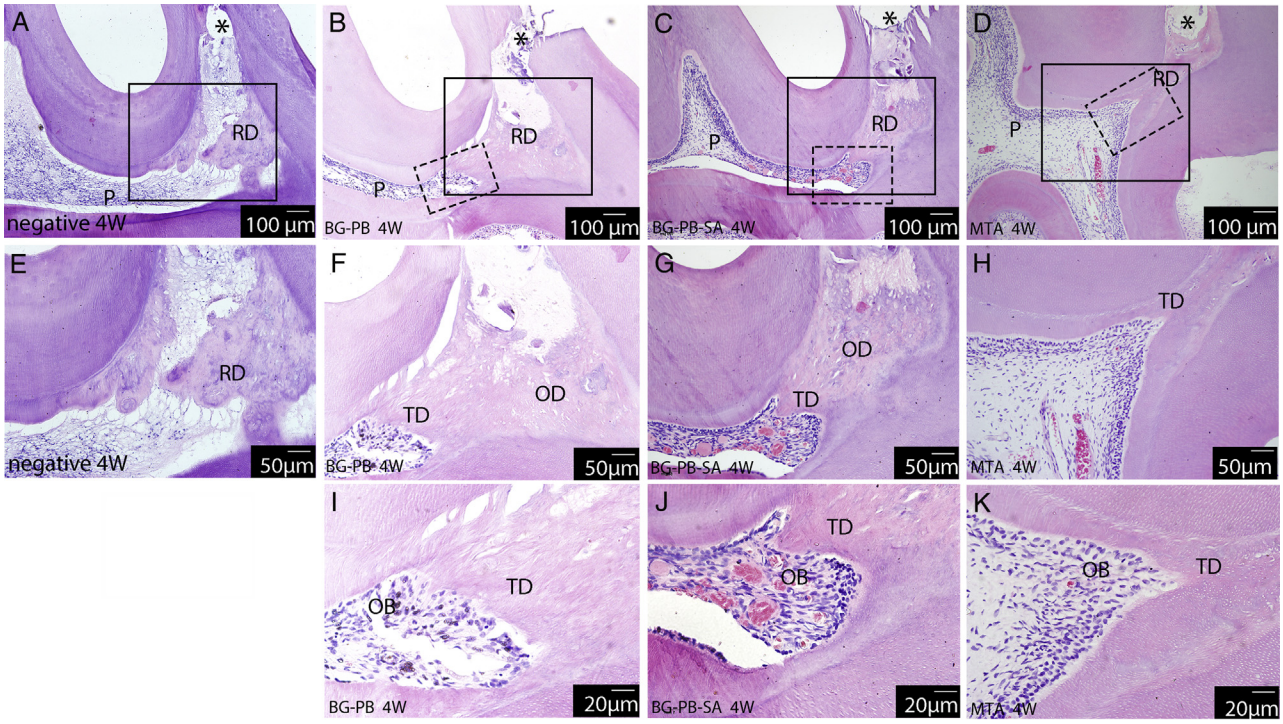

Figure 2. Hematoxylin-eosin staining evaluation of the effects of the (*A*) negative control, (*B*) BG-PB, (*C*) BG-pa, and (*D*) MTA groups on direct pulp capping assay at 4 weeks. *E–H* present a high-magnification view of the area demarcated by the *black solid rectangles* in *A–D*. *I–K* present a high-magnification view of the area demarcated by the *black dotted rectangles* in *B–D*. P, pulp; *, pulp exposure; RD, reparative dentin; TD, tubular dentin; OD, osteoid dentin; OB, odontoblastlike cells.

The osteoid dentin layer indicated a fairly rapid reparative process. A layer of polarizing odontoblastlike cells was also aligned along the inner side of the dentin bridge (Fig. 2*I–K*). The adjacent pulp appeared nearly normal. In MTA group, heavy hard tissue formation was also observed. Three quarters of the specimens showed tubular structures, whereas the remaining one quarter showed no tubular structure. The adjacent pulp showed slight to moderate inflammatory responses. Our results in the MTA group are consistent with those of other studies (5, 8, 14).

In summary, BG pulp capping materials and MTA exhibited similar favorable cellular and inflammatory pulp responses when applied on mechanically exposed rat pulps. Therefore, BG pulp capping materials are promising pulp capping materials. Further studies should investigate the physical properties of BG pulp capping materials.

Acknowledgments

Yunzi Long and Siyi Liu contributed equally to this study.

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The authors deny any conflicts of interest related to this study.

References

1. Cho SY, Seo DG, Lee SJ, et al. Prognostic factors for clinical outcomes according to time after direct pulp capping. J Endod 2013;39:327–31.
2. Aguilar P, Linsuwanont P. Vital pulp therapy in vital permanent teeth with cariously exposed pulp: a systematic review. J Endod 2011;37:581–7.
3. Li Z, Cao L, Fan M, et al. Direct pulp capping with calcium hydroxide or mineral trioxide aggregate: a meta-analysis. J Endod 2015;41:1412–7.
4. Tran XV, Gorin C, Willig C, et al. Effect of a calcium-silicate-based restorative cement on pulp repair. J Dent Res 2012;91:1166–71.
5. Louwakul P, Lertchirakarn V. Response of inflamed pulps of rat molars after capping with pulp-capping material containing fluocinolone acetonide. J Endod 2015;41:508–12.
6. Lee WC, Oh JH, Park JC, et al. Performance of electrospun poly(ε-caprolactone) fiber meshes used with mineral trioxide aggregates in a pulp capping procedure. Acta Biomater 2012;8:2986–95.
7. Zhu L, Yang J, Zhang J, et al. *In vitro* and *in vivo* evaluation of a nanoparticulate bioceramic paste for dental pulp repair. Acta Biomater 2014;10:5156–68.
8. Shi S, Bao ZF, Liu Y, et al. Comparison of *in vivo* dental pulp responses to capping with iRoot BP Plus and mineral trioxide aggregate. Int Endod J 2016;49:154–60.
9. Liu SY, Wang SN, Dong YM. Evaluation of a bioceramic as a pulp capping agent *in vitro* and *in vivo*. J Endod 2015;41:652–7.
10. Zhang D, Lepparanta O, Munukka E, et al. Antibacterial effects and dissolution behavior of six bioactive glasses. J Biomed Mater Res A 2010;93:475–83.
11. Gong WY, Huang ZW, Dong YM, et al. Ionic extraction of a novel nano-sized bioactive glass enhances differentiation and mineralization of human dental pulp cells. J Endod 2014;40:83–8.
12. Wang SN, Gao XJ, Gong WY, et al. Odontogenic differentiation and dentin formation of dental pulp cells under nanobioactive glass induction. Acta Biomater 2014;10:2792–803.
13. Accorinte Mde L, Holland R, Reis A, et al. Evaluation of mineral trioxide aggregate and calcium hydroxide cement as pulp capping agents in human teeth. J Endod 2008;34:1–6.
14. Dominguez M, Witherspoon D, Gutmann J, et al. Histological and scanning electron microscopy assessment of various vital pulp-therapy materials. J Endod 2003;29:324–33.
15. Dammaschke T. Rat molar teeth as a study model for direct pulp capping research in dentistry. Lab Anim 2010;44:1–6.
16. Al-Hezaimi K, Salameh Z, Al-Fouzan K. Histomorphometrie and micro-computed tomography analysis of pulpal response to three different pulp capping materials. J Endod 2011;37:507–12.
17. Oguntebi B, Clark A, Wilson J. Pulp capping with Bioglass and autologous demineralized dentin in miniature swine. J Dent Res 1993;72:484–9.
18. Salako N, Joseph B, Ritwik P, et al. Comparison of bioactive glass, mineral trioxide aggregate, ferric sulfate, and formocresol as pulpotomy agents in rat molar. Dent Traumatol 2003;19:314–20.
19. Sepulveda P, Jones JR, Hench LL. Characterization of melt-derived 45S5 and sol-gel-derived 58S bioactive glasses. J Biomed Mater Res 2001;58:734–40.
20. Lei B, Chen X, Han X, et al. Unique physical–chemical, apatite-forming properties and human marrow mesenchymal stem cells (HMSCs) response of sol–gel bioactive glass microspheres. J Mater Chem 2011;21:12725–34.