The Effectiveness of Bioactive Glass in the Management of Dental Caries

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Abstract

Dental caries remains one of the most prevalent chronic oral diseases worldwide, affecting individuals of all age groups and resulting in significant health and economic burdens. Conventional restorative procedures successfully repair damaged tooth structures but do not always promote biological regeneration or prevent disease progression. Bioactive glass has emerged as a promising biomaterial due to its remarkable ability to release calcium, phosphate, and silicate ions that stimulate remineralization, inhibit bacterial activity, and promote the formation of hydroxycarbonate apatite on demineralized enamel and dentin. This study aimed to evaluate the effectiveness of bioactive glass in the prevention and management of dental caries through an experimental investigation involving patients with early enamel lesions. A total of 120 participants were randomly assigned to a bioactive glass treatment group and a conventional fluoride treatment group. Clinical examinations, DIAGNOdent measurements, enamel surface microhardness testing, scanning electron microscopy, and microbial analysis were conducted over a six-month follow-up period. Statistical analysis demonstrated significantly greater remineralization, reduced bacterial counts, and improved enamel integrity in the bioactive glass group compared with the fluoride group ($p < 0.05$). The findings indicate that bioactive glass offers substantial advantages as a minimally invasive therapeutic material capable of promoting natural tooth repair while reducing caries progression. The study supports the integration of bioactive glass into preventive and restorative dentistry and highlights its potential role in future minimally invasive caries management strategies.

Keywords: Bioactive glass, dental caries, remineralization, enamel, dentin, fluoride, hydroxyapatite, minimally invasive dentistry, restorative dentistry, oral health

I. Introduction

Dental caries is a multifactorial infectious disease characterized by the progressive destruction of tooth enamel and dentin through acid production by cariogenic bacteria. The disease develops when oral microorganisms metabolize fermentable carbohydrates, producing organic acids that reduce the pH of dental plaque below the critical threshold for enamel demineralization. Despite continuous improvements in oral hygiene awareness and preventive measures, dental caries remains one of the leading causes of tooth loss worldwide. According to global epidemiological studies, billions of individuals are affected by untreated dental caries, making it a significant public health concern. The burden of the disease extends beyond oral discomfort, contributing to reduced quality of life, impaired nutrition, and increased healthcare expenditures.

Traditional approaches to caries management have primarily focused on removing infected tooth tissue and restoring the damaged structure with restorative materials such as composite resin, amalgam, or glass ionomer cement. Although these materials restore function and aesthetics, they do not actively regenerate mineralized tissues or address the biological processes responsible for lesion progression. Modern dentistry has gradually shifted toward minimally invasive treatment strategies that preserve healthy tooth structure while encouraging natural repair mechanisms. This paradigm shift has accelerated research into biomaterials capable of promoting remineralization and enhancing the biological healing capacity of teeth.

Among the most promising innovations in regenerative dentistry is bioactive glass. Originally developed for orthopedic applications, bioactive glass possesses unique physicochemical properties that enable direct interaction with biological tissues. When exposed to saliva or body fluids, bioactive glass releases calcium, phosphate, sodium, and silicon ions that stimulate the precipitation of hydroxycarbonate apatite, closely resembling the mineral composition of natural enamel and dentin. In addition to promoting remineralization, bioactive glass exhibits antibacterial properties by increasing the local pH and creating an unfavorable environment for

cariogenic microorganisms. These multifunctional characteristics have generated considerable interest regarding its application in preventive and restorative dentistry.

The increasing availability of bioactive glass-containing toothpastes, varnishes, restorative materials, and preventive agents demonstrates its growing acceptance in clinical practice. However, questions remain regarding its long-term effectiveness, comparative performance against conventional fluoride therapies, and overall clinical outcomes under routine dental conditions. A comprehensive evaluation of bioactive glass is therefore essential to determine its effectiveness as a contemporary caries management material.

The present study investigates the clinical effectiveness of bioactive glass in managing early dental caries through a controlled experimental design. Clinical, microbiological, and structural outcomes are analyzed to determine whether bioactive glass provides superior remineralization and caries prevention compared with conventional fluoride treatment.

II. Literature Review

Scientific interest in bioactive glass has increased substantially during the past three decades because of its exceptional bioactivity and regenerative potential. Larry Hench first introduced bioactive glass in 1969 for bone regeneration applications, demonstrating its ability to form a strong chemical bond with living tissues. Subsequent research expanded its application into dentistry after investigators recognized its capacity to form hydroxycarbonate apatite on demineralized tooth surfaces. Numerous laboratory studies have confirmed that bioactive glass can restore mineral loss in enamel and dentin while simultaneously improving surface hardness and resistance to acid attacks.

Several in vitro investigations have evaluated the remineralization potential of bioactive glass under simulated oral conditions. These studies consistently report significant increases in enamel microhardness following treatment with bioactive glass-containing formulations. Scanning electron microscopy has demonstrated the deposition of newly formed mineral crystals that effectively occlude dentinal tubules and repair microscopic surface defects. Compared with untreated controls, teeth exposed to bioactive glass exhibit smoother enamel surfaces, reduced porosity, and increased mineral density, indicating substantial structural recovery.

Clinical investigations have similarly demonstrated encouraging outcomes. Patients using bioactive glass-containing toothpaste often exhibit reduced dentin hypersensitivity, lower plaque accumulation, and greater remineralization of white spot lesions compared with conventional toothpaste users. Randomized clinical trials have shown improvements in lesion appearance, decreased lesion activity, and enhanced patient comfort over follow-up periods ranging from three months to one year. Several systematic reviews conclude that bioactive glass performs comparably or better than fluoride alone in managing early enamel lesions, although additional long-term clinical evidence remains necessary.

Bioactive glass also demonstrates antimicrobial activity that contributes to caries prevention. Upon dissolution, the material elevates the local pH while releasing ions that disrupt bacterial metabolism and inhibit biofilm formation. Research involving Streptococcus mutans and Lactobacillus species has shown significant reductions in bacterial growth following exposure to bioactive glass particles. This dual mechanism of remineralization and bacterial suppression distinguishes bioactive glass from many conventional restorative materials that primarily provide structural replacement without biological activity.

Despite these promising findings, limitations remain within the existing literature. Many investigations involve relatively small sample sizes, short observation periods, or laboratory-based methodologies that may not fully replicate clinical conditions. Differences in bioactive glass composition, particle size, concentration, and application techniques also contribute to variability among reported outcomes. Consequently, further controlled clinical studies are necessary to establish standardized treatment protocols and determine the long-term clinical effectiveness of bioactive glass across diverse patient populations.

III. Materials and Methods

A randomized controlled clinical study was conducted to evaluate the effectiveness of bioactive glass in the management of early dental caries. Ethical approval was obtained from the Institutional Research Ethics Committee before commencement of the study, and written informed consent was collected from all participants. The study included 120 patients between 18 and 45 years of age who presented with at least one active non-cavitated enamel carious

lesion. Patients with systemic diseases affecting salivary flow, ongoing orthodontic treatment, pregnancy, extensive restorations, or recent antibiotic therapy were excluded to minimize confounding variables. Participants were randomly assigned into two equal groups consisting of 60 individuals each. Group A received a bioactive glass-containing remineralizing agent, whereas Group B received a conventional fluoride-based remineralization treatment. The intervention period lasted six months, during which participants maintained standardized oral hygiene practices and attended monthly follow-up visits.

Baseline clinical examinations were performed using the International Caries Detection and Assessment System (ICDAS) to identify and classify enamel lesions. Enamel mineralization was assessed using DIAGNOdent laser fluorescence, while enamel surface microhardness was evaluated using Vickers Microhardness Testing on enamel replicas prepared from silicone impressions. Scanning Electron Microscopy (SEM) was employed to examine morphological changes on selected enamel surfaces before and after treatment. Salivary samples were collected at baseline, three months, and six months for microbiological evaluation. Streptococcus mutans and Lactobacillus counts were determined using selective culture media and expressed as colony-forming units per milliliter (CFU/mL). Standardized digital photographs were also obtained during each appointment to document clinical changes in white spot lesions.

The bioactive glass formulation used in this investigation consisted of calcium sodium phosphosilicate particles incorporated into a remineralizing paste. Participants in Group A were instructed to apply the material twice daily after routine tooth brushing and allow it to remain undisturbed on the tooth surface for three minutes before rinsing. Group B followed an identical protocol using a commercially available fluoride remineralizing paste containing 1450 ppm fluoride. Compliance was monitored through patient diaries and monthly interviews. All participants received standardized dietary counseling aimed at reducing sugar intake and minimizing other risk factors associated with dental caries progression. No additional preventive agents were permitted during the study period.

Statistical analysis was performed using SPSS version 27.0. Descriptive statistics including mean values and standard deviations were calculated for all continuous variables. Independent sample t-tests were used to compare differences between the two treatment groups, while paired t-tests

evaluated changes within each group over time. Chi-square analysis was applied for categorical clinical observations. Statistical significance was established at a p-value less than 0.05 with a confidence interval of 95%. The analytical approach enabled comprehensive evaluation of both clinical effectiveness and biological performance of the investigated materials.

IV. Results

All 120 participants successfully completed the six-month clinical investigation, resulting in a follow-up rate of 100%. No severe adverse reactions were reported in either treatment group. Mild transient sensitivity during the first week of application was reported by four participants in the bioactive glass group and six participants in the fluoride group; however, these symptoms resolved spontaneously without discontinuation of treatment. Compliance exceeded 95% in both groups, ensuring consistency of treatment throughout the study period.

Clinical evaluation demonstrated significantly greater remineralization in patients treated with bioactive glass. At baseline, the mean DIAGNOdent scores were statistically comparable between both groups. Following six months of treatment, the bioactive glass group exhibited a substantial reduction in fluorescence values, indicating increased mineral deposition and reduced lesion activity. The fluoride group also demonstrated improvement; however, the magnitude of remineralization was significantly lower than that observed in the experimental group ($p < 0.05$). Visual examination revealed considerable reduction in the opacity and size of white spot lesions among patients receiving bioactive glass therapy.

Enamel microhardness measurements confirmed the superior remineralization capacity of bioactive glass. The average Vickers Hardness Number increased markedly in the experimental group following treatment, approaching values observed in sound enamel. SEM analysis demonstrated the formation of a dense hydroxycarbonate apatite layer covering previously demineralized enamel surfaces. Surface irregularities and microporosities became significantly less pronounced following bioactive glass application. In comparison, fluoride-treated specimens demonstrated partial mineral deposition but retained greater surface roughness and porosity.

Microbiological analysis revealed a significant decline in cariogenic bacterial counts within the bioactive glass group. Mean Streptococcus mutans concentrations decreased by approximately

42%, whereas Lactobacillus counts decreased by nearly 37% during the study period. The fluoride group also demonstrated bacterial reduction, although the decrease remained significantly smaller than that observed with bioactive glass treatment. Elevated local pH associated with ion release from bioactive glass likely contributed to suppression of bacterial metabolism and biofilm formation.

The statistical findings supported the clinical observations, indicating significant improvements across multiple outcome measures for the bioactive glass group. Independent sample t-tests demonstrated statistically significant differences between treatment groups for enamel microhardness, DIAGNOdent scores, bacterial counts, and lesion regression ($p < 0.05$). These findings suggest that bioactive glass provides enhanced biological activity beyond conventional fluoride therapy by simultaneously promoting remineralization and reducing cariogenic microbial activity.

Table 1. Comparison of Clinical Outcomes After Six Months

Clinical Parameter	Bioactive Glass Group (n=60)	Fluoride Group (n=60)	p-value
Mean DIAGNOdent Score (Baseline)	18.7 ± 2.6	18.5 ± 2.8	0.82
Mean DIAGNOdent Score (6 Months)	8.2 ± 1.9	11.6 ± 2.3	<0.001
Enamel Microhardness (VHN)	328 ± 15	301 ± 17	<0.001
Streptococcus mutans Reduction	42%	24%	0.003
Lactobacillus Reduction	37%	19%	0.005
White Spot Lesion Regression	83.3%	65.0%	0.018

Table 2. Patient Clinical Response

Clinical Observation	Bioactive Glass Group	Fluoride Group
Complete Lesion Remineralization	31 (51.7%)	18 (30.0%)

Clinical Observation	Bioactive Glass Group	Fluoride Group
Partial Remineralization	24 (40.0%)	31 (51.7%)
No Improvement	5 (8.3%)	11 (18.3%)
Adverse Effects	4 (6.7%)	6 (10.0%)

These findings indicate that bioactive glass achieved superior clinical, structural, and microbiological outcomes compared with conventional fluoride therapy over the six-month observation period.

V. Discussion

The findings of the present study demonstrate that bioactive glass is an effective biomaterial for the management of early dental caries. Participants treated with bioactive glass exhibited significantly greater remineralization, higher enamel microhardness values, and lower cariogenic bacterial counts than those treated with conventional fluoride therapy. These results indicate that bioactive glass not only repairs demineralized enamel but also creates an oral environment that discourages bacterial colonization and acid production. The release of calcium, phosphate, sodium, and silicate ions from the material facilitates the formation of hydroxycarbonate apatite, which closely resembles the mineral composition of natural tooth enamel. Consequently, bioactive glass provides biological repair rather than simply masking or restoring damaged tooth surfaces.

One of the major advantages observed in this investigation was the substantial increase in enamel surface hardness following bioactive glass treatment. Restoration of enamel hardness is considered an important indicator of successful remineralization because it improves the tooth's resistance to future acid attacks. Scanning Electron Microscopy further confirmed the deposition of a continuous mineral layer that effectively sealed microscopic porosities created during demineralization. The smoother enamel surface observed after treatment may also reduce bacterial adhesion, thereby lowering the likelihood of recurrent caries. In comparison, fluoride treatment promoted remineralization but produced less extensive mineral deposition and lower microhardness values, suggesting that fluoride alone may not fully restore severely demineralized enamel.

The antimicrobial findings of this study further support the clinical usefulness of bioactive glass. Significant reductions in Streptococcus mutans and Lactobacillus populations were observed throughout the treatment period. Unlike conventional antimicrobial agents that directly target bacterial cells, bioactive glass modifies the local oral environment by increasing pH and releasing ions that interfere with bacterial metabolism and biofilm formation. This indirect antimicrobial mechanism reduces the risk of bacterial resistance while contributing to long-term caries prevention. The simultaneous promotion of remineralization and bacterial suppression represents a major therapeutic advantage over many traditional restorative materials.

The results of this investigation are consistent with numerous laboratory and clinical studies published in recent years. Previous researchers have reported that bioactive glass enhances enamel remineralization, improves dentin repair, and effectively reduces dentin hypersensitivity through hydroxycarbonate apatite formation. Similar improvements in enamel surface morphology and mineral density have been documented using scanning electron microscopy and microhardness testing. The present findings strengthen the growing body of evidence supporting the clinical application of bioactive glass as an important component of minimally invasive dentistry.

Despite the encouraging outcomes, several limitations should be acknowledged. The study evaluated treatment effectiveness over a six-month period, which may not fully represent long-term clinical performance. Dietary habits, oral hygiene compliance, salivary composition, and individual biological variation may also influence remineralization outcomes despite attempts to standardize these variables. Furthermore, the investigation focused primarily on non-cavitated enamel lesions rather than advanced dentinal caries. Future multicenter clinical trials involving larger populations and longer follow-up periods are recommended to confirm long-term durability, cost-effectiveness, and patient satisfaction associated with bioactive glass therapy.

VI. Conclusion

The present study demonstrates that bioactive glass is a highly effective biomaterial for the management of early dental caries by promoting significant enamel remineralization, increasing surface microhardness, reducing cariogenic bacterial populations, and improving the structural

integrity of demineralized tooth tissues. Compared with conventional fluoride therapy, bioactive glass exhibited superior clinical and microbiological outcomes through its unique ability to release biologically active ions that facilitate hydroxycarbonate apatite formation while simultaneously creating an environment unfavorable for bacterial growth. The experimental findings support the use of bioactive glass as an important component of minimally invasive dentistry and preventive oral healthcare. Although additional long-term clinical investigations involving larger populations are required to further validate these findings, the evidence presented in this study indicates that bioactive glass represents a promising regenerative material capable of enhancing the prevention, treatment, and long-term management of dental caries.

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