Submitted: 01 November, 2023 Accepted: 11 January, 2024 Published: 03 July, 2024 DOI:10.22514/jocpd.2024.089

Journal of Clinical Pediatric Dentistry

ORIGINAL RESEARCH

Comparison of the physical properties of glass ionomer modified with silver phosphate/hydroxyapatite or titanium dioxide nanoparticles: *in vitro* study

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Abstract

Glass ionomer cements (GICs) are the common materials employed in pediatric dentistry because of their specific applications in class I restorations and atraumatic restoration treatments (ART) of deciduous teeth in populations at high risk of caries. Studies show a limited clinical durability of these materials. Attempts have thus been made to incorporate nanoparticles (NPs) into the glass ionomer for improving resistance and make it like the tooth structure. An *in vitro* experimental study was conducted using the required samples dimensions and prepared based on the test being carried out on the three groups with or without the modification of light-cured glass ionomer. Samples were grouped as follows: control group (G1_C), 2% silver phosphate/hydroxyapatite NPs group (G2_SPH), and 2% titanium dioxide NPs group (G3_TiO_2). The physical tests regarding flexural strength (n = 10 per group), solubility (n = 10 per group), and radiopacity (n = 3 per group) were performed. The data were analyzed by Shapiro Wilks test, and one-way analysis of variance (one-way ANOVA), and multiple comparisons by *post hoc* Tukey's test. The p-value of < 0.05 was considered significant. No statistically significant difference was observed between the control group (G1_C) and (G2_SPH) (p = 0.704) in the flexural strength test, however differences were found between G2_SPH and G3_TiO_2 groups, ANOVA (p = 0.006); *post hoc* Tukey's test (p = 0.014). Pertaining to the solubility, G2_SPH obtained the lowest among the three groups, ANOVA (p = 0.010); *post hoc* Tukey's test (p = 0.009). The three study groups obtained an adequate radiopacity of $>$1 mm Al, respectively. The resin-modified glass ionomer cement (RMGIC) was further modified with 2% silver phosphate/hydroxyapatite NPs to improve the physical properties such as enhancing the solubility and sorption without compromising the flexural strength and radiopacity behavior of modified RMGIC. The incorporation of 2% titanium dioxide NPs did not improve the properties studied.

Keywords

Glass ionomer; Nanoparticles; Silver phosphate; Hydroxyapatite; Titanium dioxide; Physical properties

1. Introduction

In Mexico, 85% children have cavities according to the latest report from National Epidemiological Surveillance System of Oral Pathologies (SIVEPAP, 2019) [1]. Various national and international guidelines such as NOM-013-SSA2-2015 [2], Latin American Association of Pediatric Dentistry (ALOP) [3], and the American Academy of Pediatric Dentistry (AAPD) [4] have recommended the usage of GICs for class I restorations and atraumatic restoration treatments (ART) of deciduous teeth in populations at high risk of caries [5].

GICs are the materials with favorable characteristics such as tooth adhesion, biocompatibility, and fluoride release [6]. They can be utilized as luting agent and restorative material. However, the integrity of this material is compromised by the disadvantages like fractures, low resistance to wear [7], and susceptible to dehydration and high solubility [8]. The resin-modified glass-ionomer cements (RMGICs) were developed to overcome these limitations. Unlike the conventional GICs, they are characterized by high fracture and wear resistance. Furthermore, they are less susceptible to moisture and solubility [9].

RMGIC durability can be influenced by properties such as flexural strength, water sorption to change the material volume and deterioration of matrix structure, and solubility affecting its longevity, stability and biocompatibility. Previous studies have modified the GICs by adding hydroxyapatite [10], titanium [7], zirconia, aluminum oxide [11], and more recently plant extracts [12] to improve the physical and mechanical characteristics. However, conflicting results were obtained pertaining to the influence on physical properties.

Various nanostructures have emerged which include silver phosphate (Ag_3PO_4) as a form of silver compound having antimicrobial and antifungal properties proportional to the released silver ions. They interact with the proteins and enzymes of bacteria and disrupt the cell wall and bacterial membranes [6]. Furthermore, hydroxyapatite is one of the bioceramics used in medical products for the teeth remineralization [13]. This improves the resistance to bending and adhesion of cement as it has a similar structure to that of teeth apatite. Moreover, it increases the bioactive capacity of modified materials [10]. On the other hand, titanium dioxide (TiO_2) NPs can potentiate antibacterial activity, improve the release and recharge capacity of fluoride [14], and enhance the compressive strength [5].

The silver compound in combination with hydroxyapatite has the aforementioned characteristics, however they have been little studied. The effects of adding metal NPs to RMGICs are considered to ensure that these modifications do not cause deleterious impact on the materials in pediatric dentistry.

The purpose of this study was to investigate the physical characteristics such as flexural strength, elastic modulus, sorption, solubility and radiopacity of modified RMGIC with two NPs: silver phosphate/hydroxyapatite (Ag_3PO_4/HA) (SPH) NPs or titanium dioxide (TiO_2) NPs. The null hypothesis was that the RMGICs modified with nanostructures had physical properties similar to those of RMGICs.

2. Materials and method

2.1 Materials selection

An *in vitro* experimental study was conducted by following the sequence of procedures and techniques as shown in Fig. 1. RMGIC (Prime Dent Light Cure Glass Ionomer Restorative™; Chicago, IL, USA), it was used from the same batch (BZF09Y), exp. (06/24) in order to avoid biases. In addition, two different types of nanoparticles were selected: (a) 2% silver phosphate/hydroxyapatite (SPH) NPs (made in lab according to Rameshbabu *et al.* [15] method), and (b) 2% titanium dioxide (TiO_2) NPs (Sigma-Aldrich; St. Louis, MO, USA).

2.2 Nanoparticles incorporation into RMGIC and specimen preparation

An analytical balance (Adventurer Pro balance, Ohaus, Pine Brook, NJ, USA) with an accuracy of 0.0001 g was used to weigh the nanoparticles powders. For the preparation of experimental groups: 2 wt% of silver phosphate/hydroxyapatite or titanium dioxide NPs were added to the RMGIC powder, they were blended for homogeneity by the vortex mixer (Maxi Mix II, M37615, Thermo Scientific, China) for 1 min before mixing with the liquid. Conventional RMGIC or modified RMGICs specimens were prepared using the indicated proportion of 1 powder/1 liquid Prime Dent Light Cure Glass Ionomer Restorative™ at room temperature [16]. They were mixed manually for 20 s with plastic spatula.

RMGIC or modified RMGICs were packed into a specific mold for each test and covered by Mylar® film. They were compressed by a glass plate with 500 g load to obtain a completely flat surface. RMGICs were polymerized by Bluephase N100-240 v lamp (Ivoclar Vivadent; Madrid Spain) at 1200 mW/cm^2 for 20 s per each side. The intensity of light source was checked after every five samples by a light radiometer (LM-1 Woodpecker Radiometer, Guilin, Guangxi, P.R. China), and stored at 37 °C for 24 h.

2.3 Experimental groups

Sixty-nine samples were distributed in three groups: G1_C. Control: (n = 23); G2_SPH: (n = 23) RMGIC plus 2% silver phosphate/hydroxyapatite NPs; G3_TiO_2: (n = 23) RMGIC plus 2% titanium dioxide NPs. The properties by group were evaluated: flexural strength test (n = 10 p/g), solubility test (n = 10 p/g), and radiopacity test (n = 3 p/g).

2.4 Flexural strength test

RMGIC or modified RMGICs bar-shaped samples with dimensions of 25 mm length × 2 mm width × 2 mm height were prepared in a stainless-steel mold as per the procedures described in ISO 9917-2:2017 [17].

The samples were subjected to three-point flexural test on universal testing machine (Instron 5567; Instron, Norwood, MA, USA) at crosshead speed of 1.0 mm/min. The maximum loads for sample fracture were recorded. The flexural strength and elasticity modulus were calculated using standard formula [17]:

$$FS = \frac{3 \cdot F \cdot 1}{2 \cdot w \cdot h^2}$$

Where F is the load at fracture, 1 is the distance between the supports (20.0 mm), w is the specimen width, and h is the specimen height.

2.5 Sorption and solubility test

RMGIC or modified RMGICs were prepared in a stainless-steel mold of 10 mm internal diameter and 1.5 mm height. The samples were weighed and placed in suspension *via* the wire baskets in 10 mL glass bottle, that they remained untouched. Ten mL tri-distilled water was added. The flask was closed and kept at 37 °C for 24 h. They were taken out and weighed. The excess water was removed and weighed again. The samples were weighted daily until the vials weight was stabilized with no variation of >0.001 g for three consecutive days. The amount of solubilized material was expressed in percentage by the following formulas [18]:

$$A\ (sorption)\ =\ m_1 - m_2/V$$

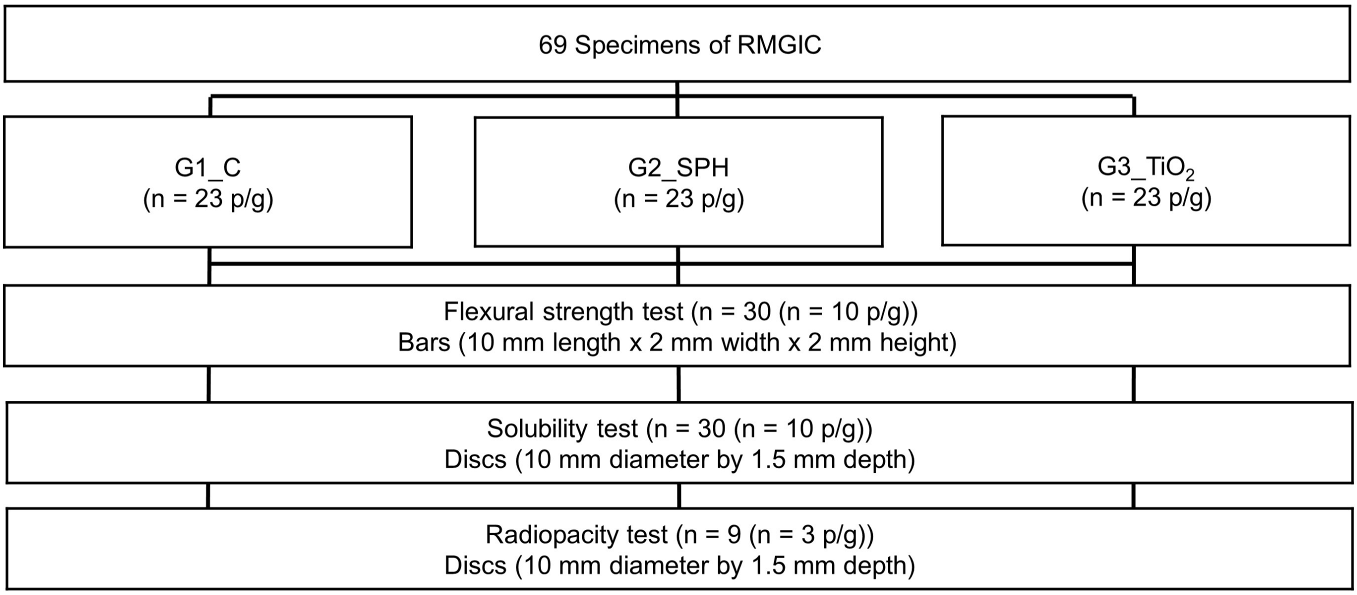

FIGURE 1. Diagram of the parameters and techniques. G1_C: control; G2_SPH: silver phosphate/hydroxyapatite; G3_TiO_2: titanium dioxide; RMGIC: resin-modified glass-ionomer cement.

$$S\ (solubility)\ =\ m_0 - m_2/V$$

Where, m_0 is the weight recorded before placing the samples in water; m_1 is the weight recorded after storage in water and m_2 is the weight recorded after storage and drying, V is the volume.

2.6 Radiopacity test

RMGIC or modified RMGICs were prepared in a stainless-steel mold of 10 mm internal diameter and 1 mm height, kept for 24 h. Samples from all groups were placed in the center of occlusal radiograph along with the radiopacity indicator stepped aluminum rack (at least 98% pure, 50 mm long $\times$ 20 mm wide, with thickness of 0.5–5.0 mm). The irradiation was made at 65 $\pm$ 5 kV *via* X-ray apparatus (X MIND DC-Satelec Acteon; Getafe, Madrid, Spain) at 30 cm distance of the film from focal point (distance was standardized with an acetate cylinder) and exposure of 0.15 s.

The radiograph was developed by following the sequential times of 15 s for developer, 15 s in water, 3 min in fixer, and 15 s in water. The radiograph was dried and placed in the center of negatoscope and digitized.

The image was analyzed by Image J 1.44 program (Rasband WS, ImageJ; U.S. National Institutes of Health, Bethesda, MD, USA). The radiographic density was assessed based on the gray tones. The radiopacity values were determined according to the radiographic density (shades of gray) and converted to millimeters of aluminum (mm Al). The conversion was performed as per the following formula of Vivan [19]:

$$Radiopacity\ (mm\ Al) = ((A \times 2)/B) + Al\ mm\ immediately\ below\ the\ RDM$$

Where A is the radiographic density of the material RDM—the radiopacity density in the grey scale of the aluminum step-wedge increment immediately below the RDM, and B is the radiopacity density in the grey scale of the aluminum step-wedge increment immediately below the RDM and + mm of aluminum of the rack corresponding to the RDM.

2.7 SEM and EDS evaluations

The descriptive evaluations of Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) were conducted for all the samples. Randomly chosen representative SEM (JEOL; JSM-6610LV, Tokyo, Japan) micrographs of each group (G1_C. Control, G2_SPH, G3_TiO_2) were analyzed for the chemical composition. Samples were fixed to aluminum stubs by double-sided adhesive carbon tape (SPI Supplies, USA) with the following settings: vacuum mode, low; chamber pressure, 30 Pa; electron accelerating voltage, 15 kV; spot size, 60; and work distance, 9 mm. Backscattered electrons were detected at $\times$1200 magnification. Three fields were randomly selected for observing the superficial structure. It was necessary to corroborate NPs (silver phosphate/hydroxyapatite or titanium dioxide) presence in modified RMGIC. Chemical mapping by EDS was conducted at $\times$500 magnification.

2.8 Statistical analysis

The data were analyzed by the statistical package (SPSS. 25.0; IBM, Armonk, NY, USA). Data distribution was evaluated by the Shapiro-Wilk test. Then differences in the physical properties between conventional RMGICs and modified RMGICs were assessed by one-way ANOVA followed by multiple comparisons with *post hoc* Tukey's test. The p value of < 0.05 was considered as the statistically significant difference.

3. Results

The general average and standard deviation of the properties studied are shown in Fig. 2A–E. The flexural strength results exhibited that G1_C and G2_SPH had similar values, 81.27 ± 10.54 and 81.40 ± 23.88 MPa, respectively. No statistically significant differences were found between the both groups (p = 0.704). G3_TiO_2 depicted decrease in the flexural strength of 59.32 ± 10.26 MPa compared to G1_C and G2_SPH. Statistically significant differences were found between G2_SPH and G3_TiO_2 groups, ANOVA (p = 0.006); *post hoc* Tukey's test (p = 0.014), as shown in Fig. 2A.

G1_C attained the highest mean of 8.5 ± 6.0 GPa for elastic modulus followed by G2_SPH with 6.6 ± 5.0 GPa, and G3_TiO_2 with 5.2 ± 4.0 GPa. No statistically significant differences were determined in any ANOVA group (p = 0.410), as shown in Fig. 2B.

G1_C presented a solubility of 27.43 ± 18.0 $\mu g/mm^3$, the G2_SPH of 9.41 ± 9.0 $\mu g/mm^3$, and G3_TiO_2 of 21.50 ± 6.0 $\mu g/mm^3$. Significant differences were noted between G2_SPH with respect to G1_C and G3_TiO_2, ANOVA (p = 0.010); *post hoc* Tukey's test (p = 0.009), as shown in Fig. 2C.

G1_C exhibited a value of 230.50 ± 139.0 $\mu g/mm^3$ for the sorption followed by G3_TiO_2 with 361.78 ± 176.0 $\mu g/mm^3$ and G2_SPH with 151.90 ± 90 $\mu g/mm^3$. No significant differences were found between G1_C and G2_SPH (p = 0.448), and G1_C and G3_TiO_2 (p = 0.121), however there were differences between G2_SPH and G3_TiO_2, ANOVA (p = 0.008); *post hoc* Tukey's test (p = 0.006), as shown in Fig. 2D.

G2_SPH and G3_TiO_2 groups had the same mean for radiopacity, *i.e.*, 2.7 ± 0.34 mm Al. G1_C attained the highest mean of 3.5 ± 0.60 mm Al. Significant differences were there between G1_C with respect to G2_SPH and G3_TiO_2, ANOVA (p = 0.002); *post hoc* Tukey's test (p = 0.007), as shown in Fig. 2E.

SEM and EDS were conducted for all the samples. The representative qualitative SEM micrographs of RMGICs surfaces for all the groups depicted homogeneous dispersion and distribution of chemical elements without the fractures, as shown in Fig. 3. However, G1_C surface had porosities, unlike the other two groups modified with NPs. EDS demonstrated the chemical components of G1_C, and the experimental groups (G2_SPH and G3_TiO_2). G1_C had the common elements like sodium (Na), aluminum (Al), silicon (Si) and barium (Ba). The modified RMGICs were analyzed to have phosphorus (P), calcium (Ca), silver (Ag), and titanium (Ti) ions.

4. Discussion

The metallic NPs are added in RMGICs to attain the long-term efficiency and clinical durability. The commonly employed NPs are the titanium dioxide and silver which improve certain mechanical properties like the compressive and flexural strengths [20, 21]. Silver phosphate is a form of silver compounds used for antibacterial applications, however with limited studies. It has advantages compared to the other silver compounds, such as low solubility in aqueous solutions, high antibacterial efficacy, and strong photocatalytic activity in visible light [22]. On the other hand, hydroxyapatite is the closest to mineral components of teeth [23]. Their addition in RMGIC increases the compressive strength by filling the voids of composite, prevents the defects (pores and cracks), and increases flexural strength, fluoride ion release and biocompatibility with low toxicity [8, 23, 24].

More recently, the proper integration of silver within hydroxyapatite structure may have a controlled release mechanism that assures a slow and steady release of silver ions [25], suggesting a new class of bioceramic nanomaterial for dental tooth filling applications [26]. Nowadays, there are no RMGIC commercially or experimental available that incorporate both nanoparticles (silver phosphate/hydroxyapatite) and their addition could be a restoration option that prove successful.

Conventional RMGIC Prime Dent Light Cure Glass Ionomer Restorative™ is selected since it is commonly placed in children of public health institutions in Mexico. It is aesthetic and economical for class III and class V pediatric restorations according to the manufacturer claim [16]. However, precise information is lacking regarding this conventional glass ionomer.

Evaluating the physical characteristics of dental materials is important for understanding the behavior of materials in various clinical conditions. Glass ionomer is thus subjected to flexural strength and elastic modulus evaluations which indicate the capacity of restorative material to resist high forces during the chewing process as well as prevent microleakage [7]. Furthermore, a three-point bending test is conducted in this study as per the ISO standard 9917-2:2017. It is regarded as a simulation of clinical situation involving the forces applied by opposing cusp. Moreover, it is the recommended test for evaluating the polymer-based materials [17].

Studies have compared various NPs. Kheur *et al.* [10] has incorporated different percentages of hydroxyapatite NPs (1%, 2%, 4%, 6% and 8%). Elsaka *et al.* [27], and García-Contreras *et al.* [7] have added 3% and 5% titanium dioxide NPs. It is observed that the flexural strength is improved compared to the non-reinforced group. However, no statistically significant differences are found between the control group and group modified with 2% silver phosphate/hydroxyapatite. There is statistical difference in the group modified with 2% titanium dioxide which depicts a decrease in flexural strength. The obtained values are similar to those reported by Mansour *et al.* [8]. It can be attributed to the added amounts of only 2% into RMGIC and the presence of voids in cement matrix, formed by the inclusion of air during cement mixing. These voids may act as stress raisers and concentrators, and ultimately weaken the mechanical properties of set cements. According to Elsaka [27], the best percentages are 3% and 5% of TiO_2 NPs which improve certain mechanical properties compared to the unmodified RMGIC. Moreover, the amounts of $>7\%$ decrease them because of the insufficient ionomer to hold relatively large amount of TiO_2 NPs.

The elastic modulus describes relationship between stress and deformation of a material undergoing given load [28]. The elastic modulus of materials should be like that of dental tissue and low enough to withstand deformations and prevent fracture of the cusps [29]. The restorations in posterior teeth must have an elastic modulus equal to or greater than that of

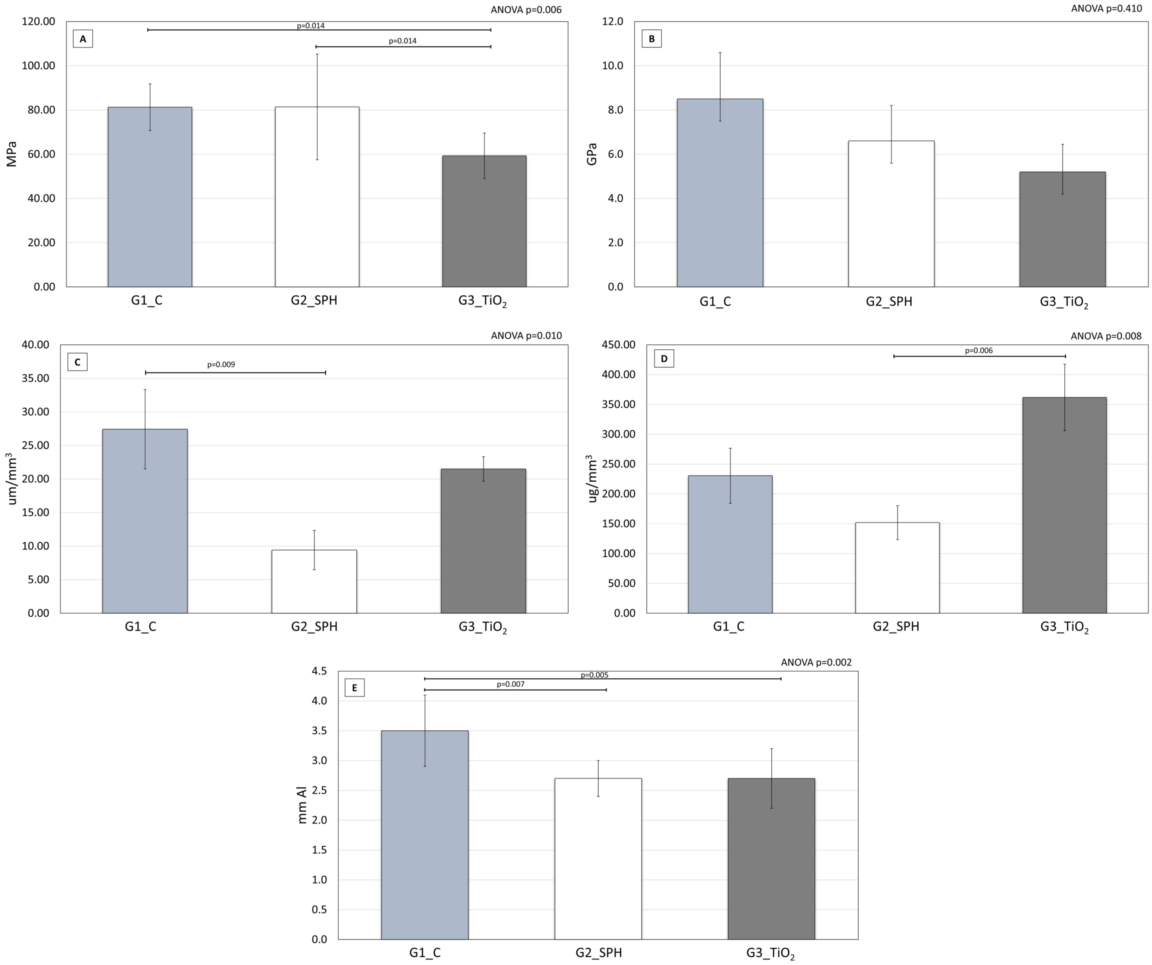

FIGURE 2. Comparison of three groups: G1_C: control; G2_SPH: silver phosphate/hydroxyapatite; G3_TiO_2: titanium dioxide with respect to (A) flexural strength (MPa), (B) elastic modulus (GPa), (C) solubility (μg/mm^3), (D) sorption (μg/mm^3) and (E) radiopacity (mm Al). Data within the groups are analyzed using one-way analysis of variance (ANOVA) followed by *post hoc* Tukey's test.

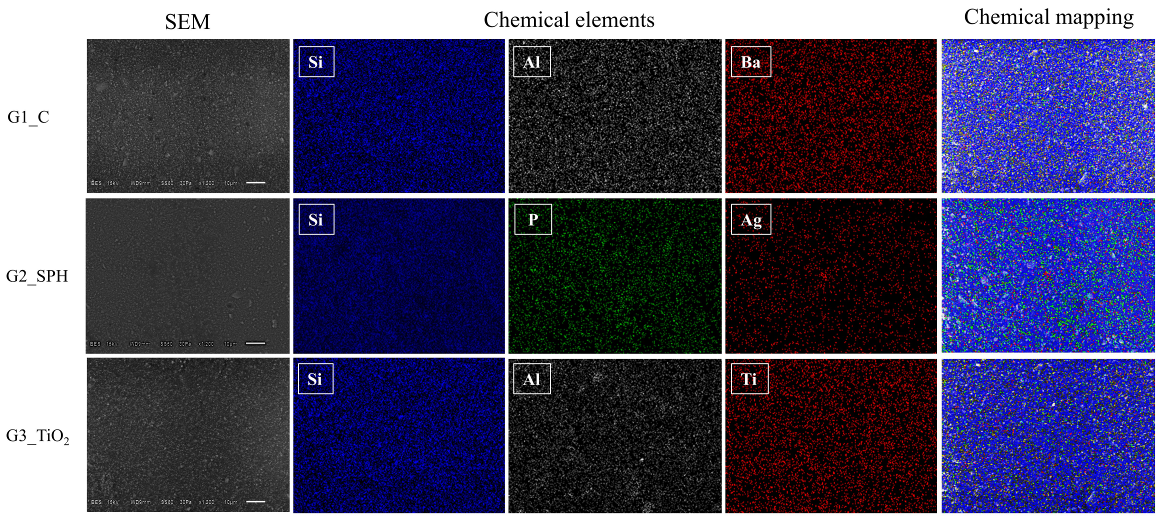

FIGURE 3. Representative SEM images of RMGICs surfaces with different nanoparticles. (Original magnification ×1200); scale bar = 10 μm. Representative chemical mapping by EDS, show a principal chemical element in conventional and modifies RMGICs, sodium (Na), aluminum (Al), silicon (Si), barium (Ba), additionally in the modified RMGICs were analyzed phosphorus (P), calcium (Ca), silver (Ag), and titanium (Ti) and chemical mapping. (Original magnification ×500); scale bar = 10 μm. G1_C: control; G2_SPH: silver phosphate/hydroxyapatite; G3_TiO_2: titanium dioxide; SEM: Scanning Electron Microscopy.

dentin, ~5.3 MPa to 13.3 GPa [30], however, in this study, the values obtained in G1_C, G2_SPH and G3_TiO_2 are below the minimum acceptable respectively. Therefore, the addition of NPs to RMGIC does not improve the elastic modulus as compared to the control group. Various clinical conditions require restorative materials of different elastic modulus. In this study, no statistically significant differences are found in any group, however it does not compromise the behavior of modified RMGICs. Hence, modified RMGIC with 2% silver phosphate/hydroxyapatite could be used in areas in which it does not receive strong occlusal loads, also have antibacterial and antibiofilm activity [6, 14, 31, 32] which would also help prevent caries lesions in interproximal areas.

The water sorption characteristics and cement solubility are the critical parameters for evaluating the bonding materials. Change in the mechanical characteristics of material directly compromises the longevity, stability and biocompatibility in the restorations [29].

RMGICs are highly sensitive to the water presence in first 24 hours. The large amount of water sorption changes the material volume and deteriorates the matrix structure [33]. It affects the properties such as strength, hardness, flexure and mechanical stability. There is a relationship between sorption and solubility. The water absorbed by reacting with the material particles produces separation and contributes to their release [33]. According to this study and following the ISO standard 4049:2009 [34], the glass ionomer modified with 2% silver phosphate/hydroxyapatite NPs attains the lowest solubility and sorption values. The enhanced physical properties in this group are due to low solubility of these particles in aqueous solutions that fill the voids between bigger glass particles in RMGIC and serve as the supplementary binding locations for polyacrylic acid, thus strengthening the GIC [35]. Modified RMGIC with 2% titanium dioxide shows the highest results of sorption and solubility, being below of the control group. This discrepancy in the relationship between solubility and sorption can be due to the factors such as type, content, and filler concentration. Moreover, it can be linked with the percentage of added NPs compared to the other studies where percentages of above 3% are added [7]. The average particle size, coupling agents, nature of filler particles, and the solvent type [30] are the characteristics for consideration when choosing the RMGIC.

The radiopacity in restorative material is important because the practitioners prefer to use dental restorative material of high radiopacity. It assists in assessing the restoration integrity, diagnose secondary caries, and differentiate between healthy tooth structures, dental material and caries [36]. In this study, the group with the highest radiopacity is the control group with 3.5 mm Al, exceeding to the ISO standard 9917-2:2017 [17]. Hidayati [37] shows that the NPs addition increases the radiopacity of GIC. The difference in percentage of added NPs affects the radiopacity. It is concluded that 4% nHA powder has the highest radiopacity compared to 2% and 3%. In this study, only 2% is employed compared to the standard study where radiopacity should be no <1 mm Al [17]. Hence, the modified groups with 2% silver phosphate/hydroxyapatite and 2% titanium dioxide are above the minimum values required by the standard, attaining 2.7 mm Al for both. The radiopacity values of dental materials used in this study are thus enough and not affected by different shades.

It can be summarized based on the above stated information that the five evaluated physical characteristics, and the modified group with 2% silver phosphate/hydroxyapatite comply and even improves the properties according to the two ISO standards [17, 34], as shown in Table 1.

This study uses SEM for investigating the surface microstructures of materials. It verifies the homogeneous distribution of NPs (silver phosphate/hydroxyapatite or titanium dioxide) in the RMGIC which otherwise has porosities on the surface of G1_C, unlike the two groups modified with NPs. This is attributed to the addition of NPs which fill the composite voids, and prevent defects (pores and cracks). The qualitative analysis *via* chemical mapping is performed by Energy Dispersive Spectroscopy for the samples under observation.

This study has certain limitations to consider. No other concentrations of NPs are measured which can have a significant yet variable effect on physical properties. However, it is observed in some pilot tests that by increasing the NPs percentage, the samples become fragile and break. Ma *et al.* [38], demonstrated that use of concentrations below one there is no decrease in physical properties, also no exhibited any significant influence on the RMGICs cytotoxicity, that is an important requirement that any dental tooth filling material must meet. Therefore, it was decided to use 2% in both experimental groups that they would be comparable in quantities. Besides, the NPs concentration in final composite must be carefully selected as higher concentration can alter the bond quality with dentin [39]. Further work is required to elucidate the effects for better comparisons.

TABLE 1. Comparison of the impact of nanostructures addition on physical properties of resin-modified glass-ionomer cements according to the ISO standards.

	ISO 9917-2:2017 [17]			ISO 4049:2009 [34]	
Material	Flexural strength	Modulus of elasticity	Radiopacity	Solubility	Sorption
Parameter	25 MPa	N/A >10.1 GPa	≥1 mm Al	<7.5 μg/mm^3	<40 μg/mm^3
G1_C	Compliance	No compliance	Compliance	No compliance	No compliance
G2_SPH	Compliance	No compliance	Compliance	Improvement	Improvement
G3_TiO_2	Compliance	No compliance	Compliance	No compliance	No compliance

Abbreviations: G1_C: control; G2_SPH: silver phosphate/hydroxyapatite; G3_TiO_2: titanium dioxide. N/A: a specific value does not apply to the standard.

Nowadays the conservative dentistry idea has become popular in caries treatment. The addition of nanomaterials represents a viable approach, which could lead to several clinical benefits, including better physical properties and the prevention of tooth decay [6]. This *in vitro* result is important for screening the conducive physical properties after the modification of RMGICs with two types of metallic NPs.

It is proposed to conduct additional laboratory evaluations regarding the bond strength, surface roughness, antibacterial properties, and cytotoxic effects. Furthermore, it is important to investigate the flour released with silver phosphate/hydroxyapatite or titanium dioxide NPs in RMGIC before being clinically tested.

5. Conclusions

This *in vitro* study along with the mentioned limitations has improved the physical properties of conventional RMGIC modified with two different nanoparticles. The incorporation of 2% titanium dioxide NPs did not improve the properties studied but keeps them according to ISO standards with exception of sorption. Furthermore, 2% silver phosphate/hydroxyapatite NPs enhances the solubility and sorption without compromising the flexural strength and radiopacity behavior of conventional RMGIC, they can be considered with potential to be used for dental tooth filling applications.

AVAILABILITY OF DATA AND MATERIALS

Not applicable.

AUTHOR CONTRIBUTIONS

BPC, AFL and MAMB—designed the research study; performed the research. BTC, BIFF, ERR and LAF—analyzed the data. BPC, MAMB, BTC and ERR—wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study was approved by the Research Committee of the Faculty of Stomatology of the Meritorious Autonomous University of Puebla, Mexico (CIFE 2021157); date of approval: 09 April 2021.

ACKNOWLEDGMENT

Thanks Biomaterials Laboratory of the Faculty of Stomatology, Innovation and Knowledge Transfer Directorate of the Meritorious Autonomous University of Puebla, Mexico for supporting this joint research project, Eric Reyes Cervantes and Erika Muñoz Gracia (DITCo) for technical assistance, “Researchers for Mexico” CONAHCyT program and Division of Postgraduate Studies and Research (DEPI), National Technological Institute of Mexico/Toluca Technological Institute, Blanca Irma Flores Ferreyra for the postdoctoral scholarship provided for National Council of Humanities, Sciences and Technologies (CONAHCyT) and Council of Science and Technology of the State of Puebla (CONCYTEP).

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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How to cite this article: Berenice Pérez-Castro, Abigailt Flores-Ledesma, Efraín Rubio-Rosas, Bernardo Teutle-Coyotecatl, Blanca Irma Flores-Ferreyra, Liliana Argueta-Figueroa, *et al*. Comparison of the physical properties of glass ionomer modified with silver phosphate/hydroxyapatite or titanium dioxide nanoparticles: *in vitro* study. Journal of Clinical Pediatric Dentistry. 2024; 48(4): 160-167. doi: 10.22514/jocpd.2024.089.