

THE EFFECT OF NANOHYDROXYAPATITE-CONTAINING TOOTHPASTE ON THE PREVENTION OF ENAMEL EROSION: AN IN VITRO PILOT STUDY

Waroonporn NITITHAMAKUL¹, Ratichanok NANTANEE² and Somkamol VANICHVATANA^{2*}

¹ Master of Science in Pediatric Dentistry, Faculty of Dentistry, Chulalongkorn University, Thailand.

² Department of Pediatric Dentistry, Faculty of Dentistry, Chulalongkorn University, Thailand; somkamol.v@chula.ac.th (Corresponding Author)

ARTICLE HISTORY

Received: 10 April 2026

Revised: 24 April 2026

Published: 16 May 2026

ABSTRACT

Dental erosion from gastroesophageal reflux disease (GERD) poses a significant clinical challenge, as chronic exposure to gastric acid (pH 1.0-1.5) leads to progressive and irreversible enamel loss. While stannous fluoride (SnF₂) is well-established for erosion prevention, nanohydroxyapatite (nano-HAP) has emerged as a biomimetic alternative; however, evidence for its efficacy under severe, repeated acid conditions remains limited. This study aimed to compare the protective effects of nano-HAP-containing toothpastes against simulated gastric acid erosion in laboratory setting. Eighteen enamel specimens from extracted permanent molars were randomly allocated into three groups: nano-HAP-containing toothpaste (Group A), SnF₂-containing toothpaste (Group B) and non-fluoride toothpaste as negative control (Group C). Specimens underwent a five-day cycling protocol of three daily hydrochloric acid challenges (0.01 M, pH 2.2) interspersed with toothpaste treatments. Outcomes were assessed by Knoop surface microhardness (percentage surface hardness change, %SHC) and non-contact profilometry (enamel surface loss). All groups showed significant reductions in surface microhardness following erosive cycling. Group A demonstrated significantly lower %SHC than the negative control ($p = 0.034$), whereas Group B was not significantly different from either Group A or C ($p = 0.212, 0.576$, respectively). Enamel surface loss did not differ significantly among all groups ($p = 0.263$). Based on these findings, nano-HAP-containing toothpaste partially preserved enamel surface hardness under simulated GERD conditions but did not significantly reduce bulk enamel loss. These findings suggest that nano-HAP provides limited protection against severe, repetitive acid exposure, and further studies should explore combinations with fluoride or other bioactive agents to enhance anti-erosive efficacy.

Keywords: Hydroxyapatite, Tooth Erosion, Gastroesophageal Reflux, Tin Fluorides, Toothpastes

CITATION INFORMATION: Nitithamakul, W., Nantanee, R., & Vanichvatana, S. (2026). The Effect of Nanohydroxyapatite-Containing Toothpaste on the Prevention of Enamel Erosion: An *In Vitro* Pilot Study. *Procedia of Multidisciplinary Research*, 4(5), 42.

INTRODUCTION

Dental erosion is an irreversible loss of mineralized dental tissue caused by chemical dissolution of enamel without bacterial involvement (Linnett & Seow, 2001). Its prevalence ranges from 30-50% in primary teeth and 20-45% in permanent teeth (Schlueter & Luka, 2018). Among its intrinsic causes, gastroesophageal reflux disease (GERD) is of particular concern. GERD affects 2.5-33.1% of the population (Yamasaki et al., 2018), and regurgitated hydrochloric acid — with a pH as low as 1-1.5 — has been strongly associated with dental erosion, with a median prevalence of 24% in GERD patients (Pace et al., 2008).

The severity of erosion depends on the pH and composition of the refluxate, the frequency of reflux episodes, and salivary buffering capacity (Pace et al., 2008; Ranjitkar et al., 2012). Clinical consequences range from mild dentin hypersensitivity to severe loss of vertical dimension and, in children, pulpal exposure (Scaramucci et al., 2015). Alongside medical management of reflux, dental preventive strategies are important for protecting oral health from the consequence of erosion in this high-risk population (Carvalho et al., 2015; Dundar & Sengun, 2014; Patel et al., 2015).

Among fluoride-based preventive strategies, stannous fluoride (SnF_2) has been widely investigated and established as one of the most effective agents for erosion prevention. Unlike conventional sodium fluoride (NaF) or amine fluoride (AmF) — which form relatively acid-soluble calcium fluoride-like deposits — SnF_2 additionally delivers stannous ions (Sn^{2+}) that react with hydroxyapatite to form a more stable, acid-resistant protective layer on the enamel surface (Ganss et al., 2008; O'Toole et al., 2015). This dual mechanism has been confirmed across extensive in vitro and in situ studies, with systematic reviews demonstrating that SnF_2 -containing products provide significantly greater enamel protection than NaF -based counterparts under both erosive and erosive-abrasive conditions (Hove et al., 2014; Zanatta et al., 2020). Despite minor side effects such as tooth staining and astringency, SnF_2 -containing toothpastes remain a well-supported and widely recommended option for erosion prevention in high-risk patients (Hove et al., 2014; Jiemkim et al., 2023).

In parallel, bioactive agents such as nanohydroxyapatite (nano-HAP) have gained increasing attention due to their chemical similarity to enamel mineral (Karaoulani et al., 2022). Nano-HAP can deposit onto acid-softened enamel, forming a calcium-phosphate-rich layer that acts as a sacrificial barrier while supplying ions to support remineralization (Colombo et al., 2016; Poggio et al., 2017; Poggio et al., 2010). Although in vitro studies have shown improvements in surface microhardness and surface properties under moderate erosive conditions, evidence under more severe and repetitive acid challenges — such as those associated with GERD — remains limited and inconsistent (Jung et al., 2025; Karaoulani et al., 2022).

Therefore, the aim of this study was to evaluate the protective effects of a commercially available nano-HAP-containing toothpaste against simulated gastric acid erosion in laboratory setting.

LITERATURE REVIEWS

Dental Erosion and GERD

Dental erosion is the progressive, irreversible loss of dental hard tissue through acid dissolution without bacterial involvement (Linnett & Seow, 2001), presenting clinically as smooth, shiny surfaces, rounded cusps, and in severe cases, complete loss of occlusal morphology (Ganss & Lussi, 2014). Enamel loses structural integrity when pH drops below a critical level (Ganss & Lussi, 2014; Lussi et al., 2012; Shellis et al., 2014), while dentin retains its collagen matrix, resulting in a softened, sponge-like layer rather than bulk tissue loss (Ganss et al., 2004; Ganss & Lussi, 2014). Among intrinsic causes, GERD is the most prevalent, affecting 5-20% of Western and Asian populations (Bartlett, 2006; Pace et al., 2008; Scaramucci et al., 2015), with repeated gastric acid exposure (pH 1.0-1.5) leading to characteristic erosion beginning on the

palatal surfaces of maxillary incisors and progressing to lingual and occlusal surfaces, ultimately compromising vertical dimension (Scaramucci et al., 2015; Young & Tenuta, 2011). Management requires long-term control of reflux alongside dental preventive strategies, with restorative treatment deferred where possible (Dundar & Sengun, 2014; Patel et al., 2015; Scaramucci et al., 2015).

Fluoride in the Prevention of Dental Erosion

Fluoride-containing toothpastes are the most accessible preventive strategy against dental erosion, as they can be easily incorporated into daily oral hygiene. Among fluoride agents, SnF₂ shows superior anti-erosive efficacy compared NaF and AmF due to its dual mechanism of forming acid resistant surface deposits and allowing tin ion penetration into demineralized enamel, which is particularly beneficial under repeated acid exposure (Ganss et al., 2008; Hove et al., 2007). Systematic reviews of in situ trials confirm this superiority, with up to 90% reduction in erosive mineral loss reported with intensive SnF₂ (Ganss et al., 2004; Zanatta et al., 2020). However, its effectiveness is formulation dependent, as abrasives and surfactants may reduce stannous ion availability and lead to variable performance (Hove et al., 2014; Zanatta et al., 2020).

Nanohydroxyapatite in the Prevention of Dental Erosion

Among the bioactive materials investigated as adjuncts for erosion prevention, including bioactive glasses (BAGs) and casein phosphopeptide-amorphous calcium phosphate (CPP-ACP), nano-HAP has attracted particular interest owing to its biomimetic properties. Sharing the same mineral composition as dental enamel, nano-HAP is proposed to bond directly to acid-softened enamel surfaces, filling surface defects and forming a sacrificial calcium-phosphate layer that buffers incoming acid while simultaneously providing a localized source of calcium and phosphate ions to support remineralization (Colombo et al., 2016; Poggio et al., 2017; Poggio et al., 2010). Under moderate erosive conditions, this mechanism translates into measurable benefit. The study of Poggio et al. in 2010 (Poggio et al., 2010) reported significant reductions in enamel surface roughness following cyclic soft drink erosion, with nano-HAP performing comparably to a conventional fluoride toothpaste, and subsequent studies corroborated these findings by demonstrating improvements in surface microhardness recovery and further reductions in roughness, supported by SEM evidence of progressive mineral deposition on treated enamel surfaces (Colombo et al., 2016; Poggio et al., 2017). Under more aggressive or high-frequency acid challenges, however, findings have been less consistent. The study of Jung et al. in 2025 (Jung et al., 2025) found that none of the commercial nano-HAP formulations tested reduced profilometric tissue loss under high-frequency cyclic erosion, with elemental analysis suggesting that many particles consist of silica cores bearing only loosely adsorbed amorphous calcium phosphate, a structure potentially susceptible to repeated acid displacement. Similarly, the study of Karaoulani et al. in 2022 (Karaoulani et al., 2022) reported no significant reduction in surface loss under gastric acid simulation. While the evidence across studies remains inconsistent, nano-HAP continues to show promise as a biomimetic erosion-preventive agent, and further research is needed to draw more definitive conclusions about its efficacy.

Methods for Assessing Dental Erosion in the Laboratory

Methods for assessing dental erosion in the laboratory are divided into quantitative and qualitative approaches. For quantitative assessment, surface hardness is commonly used in early-stage erosion by measuring enamel resistance to indentation. Two types of indenters are used: the Knoop indenter, which penetrates shallowly (~1.5 µm) and is better for detecting superficial changes, and the Vickers indenter, which penetrates deeper (~5 µm) and may also capture readings from the underlying intact enamel (Lussi & Ganss, 2014). This method is simple and low-cost but is not suitable for dentin or advanced erosion stages (Barbour & Rees, 2004; Schlueter et al., 2011). Another quantitative method, surface profilometry, measures the

actual amount of tooth structure lost by comparing eroded areas to an untreated reference surface. It comes in two forms: contact profilometry, which uses a physical stylus and may damage softened surfaces (Field et al., 2010; Joshi et al., 2016), and non-contact profilometry, which uses laser light to scan without touching the specimen, making it safer for longitudinal studies, though translucent specimens can affect accuracy (Hara & Zero, 2008; Schlueter et al., 2011; Steiner-Oliveira et al., 2010).

For qualitative assessment, Scanning Electron Microscopy (SEM) is widely used to visually examine surface changes such as mineral dissolution, dentine tubule opening, and enamel etching at high resolution. A more advanced version, Environmental SEM (ESEM), can operate under humid conditions without requiring specimen coating, which is a major advantage for moisture-sensitive dental samples (Joshi et al., 2016; Schlueter et al., 2011). These qualitative methods are often used alongside quantitative measurements to provide a more complete picture of erosive damage.

From the literature review, the conceptual framework can be drawn as shown in Figure 1.

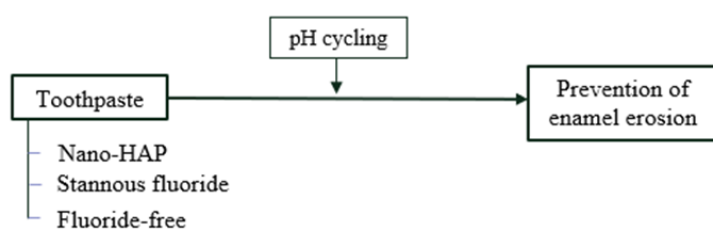


Figure 1 Conceptual Framework

RESEARCH METHODOLOGY

The study protocol was approved by the Human Research Ethics Committee and the Institutional Biosafety Committee, Faculty of Dentistry, Chulalongkorn University.

Sample size was calculated using G*Power version 3.1.9.7 with a one-way ANOVA, based on a previous study by Karaoulani et al. in 2022 (Karaoulani et al., 2022) on the protective effects of bioactive materials against enamel erosion. Based on the reported means and standard deviations of enamel surface loss, the effect size was set at 0.720. With a significance level of 0.05 and a power of 80%, a minimum of 6 specimens per group was required, giving a total of 18 specimens

Enamel samples were prepared from permanent molars extracted for medical reasons and stored in a 0.1% thymol solution. The specimens were examined under a stereomicroscope (25×) to select enamel surfaces free of cracks, caries, restorations, and other enamel defects. The enamel surfaces were then flattened using a polishing machine with silicon carbide abrasive paper to obtain a 3 mm × 3 mm experimental area, mounted in acrylic resin, and further polished with silicon carbide paper. Finally, the specimens were cleaned with deionized water for 3 minutes and dried.

Baseline surface microhardness (SH₀) was measured using a Knoop indenter (Durascan G5, ZwickRoell, Austria) with a 50 g load applied for 5 seconds. Five indentations were made at 100 μm intervals, and specimens with mean value from 270 to 350 KHN were selected. Reference indentations were placed at the enamel slab margins in areas not subjected to erosive challenge. Two regions of each specimen were covered with nail varnish to serve as reference areas for profilometric measurement. The central exposed area (1 mm × 3 mm) was subjected to the treatment.

The enamel blocks were randomly allocated into three equal groups, each assigned to a different test toothpaste as follow:

Group A: Nano-HAP-containing toothpaste without fluoride

Group B: SnF₂-containing toothpaste

Group C: Non-fluoride-containing toothpaste (negative control)

Table 1: Composition of the toothpastes selected for the study

Group	Product	Active ingredient
A	Biorepair Fast sensitive repair (Coswell S.p.A., Bologna, Italy)	16% Nano-hydroxyapatite toothpaste
B	Sensodyne rapid action (©2020 GSK groups of companies)	1450 ppm Stannous fluoride and sodium fluoride toothpaste
C	Kolbadent KIDS (Sahapan Group (Thailand) Co., Ltd.)	Non-fluoride toothpaste

The enamel specimens were subjected to a daily erosion-treatment cycle as in figure 2 over five days, consisting of three hydrochloric acid challenges (0.01 M, pH 2.2) to simulate gastric reflux and two toothpaste treatments. The specimens were preconditioned in artificial saliva for 18 hours, treated with freshly prepared toothpaste slurry (1:3 w/w) for 2 minutes after the first and third acid challenges, and stored in artificial saliva between steps and overnight. After each immersion, the specimens were rinsed with deionized water and gently blotted dry. All procedures were performed at 37°C under constant agitation (100 rpm).

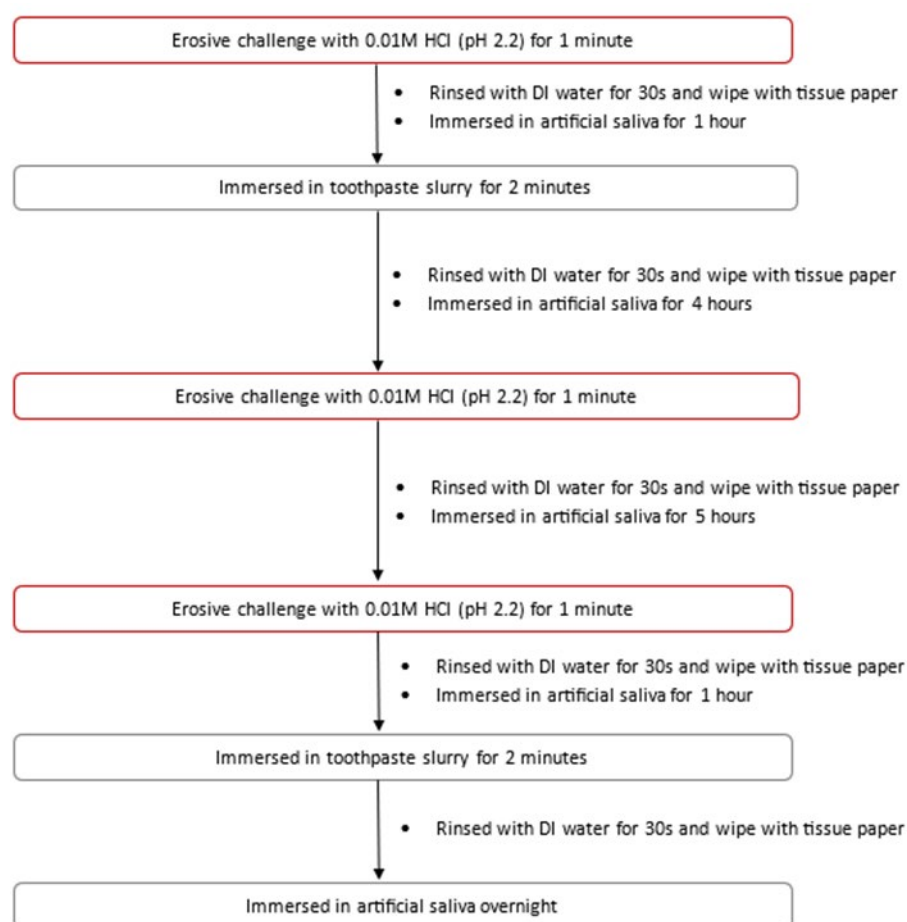


Figure 2 Flowchart of daily cycling

In this study, two methods were used to assess enamel erosion: step height measured by non-contact profilometry and surface hardness determined by Knoop microhardness testing.

Enamel surface loss was measured at the end of the experiment using non-contact profilometry (Infinite Focus SL, Alicona, Austria). After removal of the nail varnish, the depth difference between the reference areas and the treated area was determined, with the mean of three measurements was used for analysis.

Surface microhardness was remeasured at the end of the experimental period (SH_1) using a Knoop hardness tester (Durascan G5, ZwickRoell, Austria) with a 50 g load for 5 seconds. Five indentations were made at 100 μm intervals, and the percentage of surface hardness change (%SHC) was calculated as $(\%SHC = (SH_0 - SH_1) / SH_0 \times 100)$.

Descriptive statistics (mean $\pm$ standard deviation) were calculated for enamel surface loss and surface microhardness at baseline and post-experiment, as well as for the percentage of surface microhardness change. Data normality and homogeneity of variance were assessed using the Shapiro-Wilk and Levene's tests, respectively ($\alpha = 0.05$). Within-group comparisons of surface microhardness were performed using a paired t-test or Wilcoxon matched-pairs signed-rank test, as appropriate. Between-group comparisons of baseline microhardness, enamel surface loss, and percentage microhardness change were analyzed using one-way ANOVA with Tukey or Games-Howell post-hoc tests, or the Kruskal-Wallis's test with Dunn's post-hoc test, depending on data distribution and variance homogeneity.

RESEARCH RESULTS

For surface hardness measurement, the baseline surface hardness values for all experimental group were within the inclusion criteria range of 270-350 KHN with an overall mean $\pm$ standard deviation of 317.81 ± 22.48 KHN. The mean $\pm$ standard deviation for each group is shown in Table 2. The baseline data were normally distributed, and no statistically significant differences were observed among groups prior to erosive cycling.

Surface microhardness at baseline (SH_0), after erosive cycling (SH_1), and %SHC for each group were shown in Table 2. All groups showed a statistically significant reduction in surface microhardness following erosive cycling ($p < 0.01$). Statistically significant differences in %SHC were observed across the study groups ($p = 0.041$). Group A demonstrated the lowest %SHC, indicating the least hardness loss among the groups. A statistically significant difference in %SHC was found between Group A and the negative control (Group C) ($p = 0.034$), whereas no significant differences were detected among the remaining groups (Table 2).

Table 2 Mean values $\pm$ standard deviation of surface hardness analysis (n = 6) according to different treatments.

Product	SH_0	SH_1	%SHC
A	323.57 ± 25.17^a	85.91 ± 29.16^b	73.48 ± 8.74^B
B	325.43 ± 15.34^a	66.73 ± 10.65^b	79.42 ± 3.64^{AB}
C	304.43 ± 22.92^a	52.07 ± 10.33^b	82.85 ± 3.39^A

Note: Different lowercase letters indicate significant differences between SH_0 and SH_1 within the same group, whereas different uppercase letters indicate significant differences in %SHC among groups ($p < 0.05$).

For enamel surface loss, values differed across the groups after five days of erosive cycling. Group B exhibited the lowest mean surface loss, while Group C showed the highest. Despite these differences, no statistically significant differences in enamel surface loss were detected among the groups ($p = 0.263$) (Table 3).

Table 3 Mean values $\pm$ standard deviation of enamel surface loss after erosive cycle

Group	Enamel surface loss (micron)
A	1.91 ± 0.47^A
B	1.76 ± 0.66^A
C	2.30 ± 0.78^A

Note: Different uppercase letters indicate significant differences in enamel surface loss among groups ($p < 0.05$)

DISCUSSION & CONCLUSION

This study compared the protective effects of three commercially available toothpastes — nano-HAP without fluoride (Group A), SnF₂ (Group B), and non-fluoride negative control (Group C) — against simulated GERD condition over five days. All groups showed a statistically significant reduction in surface microhardness following erosive cycling. Among the groups, nano-HAP (Group A) demonstrated the lowest percentage surface hardness change, which was statistically significantly lower than the negative control, while no significant difference was found between Group A and Group B. For profilometric surface loss, Group B showed the lowest mean value, followed by Group A and Group C. However, no statistically significant differences were detected among any of the groups.

This study was designed to simulate the acid challenge pattern of GERD patients. Hydrochloric acid was selected as the erosive agent as it directly replicates the composition of gastric refluxate. Although pure gastric acid has a pH of 0.9-1.5, the pH at the oral cavity is typically higher due to salivary buffering and dilution (Hove et al., 2007) and the use of hydrochloric acid at pH 2.2 reflects the clinically reported gastric pH range in GERD patients (Pace et al., 2008). Therefore, 0.01 M hydrochloric acid at pH 2.2 was used to simulate gastric refluxate reaching the oral cavity (Hove et al., 2007). Since acid reflux episodes usually occur after meals and are typically of short duration (Shellis et al., 2011; Stenhagen et al., 2013; Wiegand & Attin, 2011), enamel specimens were subjected to three erosive challenges per day over five days to reflect the episodic and cumulative nature of acid contact in GERD patients. As enamel is softened by acid, it becomes more easily worn off by mechanical force. Therefore, it is recommended to avoid brushing for at least one hour after acid exposure (Koch & Poulsen, 2001) and assuming that brushing twice a day with fluoride toothpaste is a regular practice. Accordingly, the specimens were exposed to toothpaste slurry one hour after acid exposure in the first and last acid attacks to allow time for enamel to recover (Jiemkim et al., 2023).

Regarding stannous fluoride, Group B demonstrated the lowest mean profilometric surface loss, consistent with the established anti-erosive profile of SnF₂. The protective mechanism of SnF₂ relies on stannous ions (Sn²⁺) reacting with hydroxyapatite to form an acid-resistant tin-enriched surface deposit, substantially more stable under low-pH conditions than the calcium fluoride-like precipitates formed by conventional fluoride agents (Ganss et al., 2008; O'Toole et al., 2015). Systematic reviews have confirmed consistent superiority of SnF₂ over NaF-based products under both erosive and erosive-abrasive conditions (Hove et al., 2014; Zanatta et al., 2020). However, no statistically significant differences were detected between Group A and the other groups in the present study. A key explanation is the toothpaste vehicle itself: silica abrasives and surfactants are known to adsorb and inactivate free stannous ions before enamel contact, substantially reducing their bioavailability compared to rinse-based delivery (Hove et al., 2014; Jiemkim et al., 2023). Furthermore, since the primary anti-erosive action of SnF₂ depends on pre-erosive surface coverage (O'Toole et al., 2015), the two-minute application window between three daily acid exposures may have been insufficient for the protective deposit to withstand repeated severe challenge, diminishing the detectable benefit under the aggressive cycling protocol employed.

Regarding nano-HAP, Group A demonstrated the lowest %SHC and a statistically significant reduction compared to the negative control (Group C), indicating partial protection at the level of surface mineral integrity. This finding is consistent with the proposed biomimetic mechanism of nano-HAP, whereby particles with chemical affinity for demineralized enamel deposit onto acid-softened surfaces, forming a sacrificial calcium-phosphate layer that buffers incoming acid and provides ions to support remineralization (Colombo et al., 2016; Poggio et al., 2017; Poggio et al., 2010). However, profilometric surface loss in Group A did not differ significantly from either Group B or Group C, revealing a discrepancy between the two outcome measures. This is best understood through the difference in measurement sensitivity: microhardness reflects early-stage surface softening, whereas profilometry captures net bulk tissue loss at more advanced stages of erosion (Barbour & Rees, 2004). Nano-HAP deposits appear sufficient to partially reinforce surface mineral against indentation, yet insufficient to prevent bulk dissolution under repeated severe acid exposure — a pattern consistent with the sacrificial barrier concept, where particle re-deposition between challenges cannot keep pace with the rate of acid-driven displacement. This interpretation is supported by the study of Jung et al., a 10-day cyclic erosion model using 0.5% citric acid (pH 2.8), applied six times daily for 2 minutes per exposure. In this model, no significant reduction in profilometric tissue loss was observed with any commercial nano-HAP formulation. Elemental analysis further showed that many products contain silica cores coated with loosely adsorbed amorphous calcium phosphate, rather than true crystalline hydroxyapatite capable of stable integration with enamel (Jung et al., 2025). Consistent findings were reported by Karaoulani et al. in a cyclic erosion model using hydrochloric acid to simulate gastric acid exposure in GERD patients. In this model, a single air-abrasion pretreatment with nano-HAP powder resulted in surface loss comparable to the untreated negative control, despite SEM evidence of some apatite crystal deposition on the enamel surface (Karaoulani et al., 2022). Although that study used a single in-office application rather than the twice-daily toothpaste regimen used in the present study, both approaches showed no significant reduction in bulk tissue loss across different delivery modes and acid types. This supports the result that the protective effect of nano-HAP does not extend to preventing bulk mineral loss under sustained or high-frequency acid challenge conditions.

Several limitations of this study should be noted. The small sample size and short five-day experimental period may have been insufficient to achieve adequate statistical power, limiting the ability to detect significant differences among groups. Additionally, although silica abrasives in toothpaste are known to adsorb stannous ions and reduce their bioavailability at the enamel surface (Hove et al., 2014; Jiemkim et al., 2023; Zanatta et al., 2020), the commercial toothpaste used in Group B did not disclose its abrasive content on the product label, and the extent to which this may have affected stannous ion availability could not be controlled for in the present study. Future studies should employ larger sample sizes, longer cycle periods, and investigate the combined use of nano-HAP with fluoride or other bioactive agents to enhance anti-erosive efficacy in GERD patients.

In conclusion, nano-HAP toothpaste partially preserved enamel surface hardness and performed comparably to SnF₂ toothpaste; however, neither agent significantly prevented bulk enamel loss under repeated low-pH challenges in a five-day pH cycling model simulating GERD conditions.

REFERENCES

- Barbour, M. E., & Rees, J. S. (2004). The laboratory assessment of enamel erosion: a review. *J Dent*, 32(8), 591-602.
- Bartlett, D. (2006). Intrinsic causes of erosion. *Monogr Oral Sci*, 20, 119-139.

- Carvalho, T. S., Colon, P., Ganss, C., Huysmans, M. C., Lussi, A., Schlueter, N., Schmalz, G., Shellis, R. P., Tveit, A. B., & Wiegand, A. (2015). Consensus report of the European Federation of Conservative Dentistry: erosive tooth wear--diagnosis and management. *Clin Oral Investig*, 19(7), 1557-1561.
- Colombo, M., Beltrami, R., Rattalino, D., Mirando, M., Chiesa, M., & Poggio, C. (2016). Protective effects of a zinc-hydroxyapatite toothpaste on enamel erosion: SEM study. *Ann Stomatol (Roma)*, 7(3), 38-45.
- Dundar, A., & Sengun, A. (2014). Dental approach to erosive tooth wear in gastroesophageal reflux disease. *Afr Health Sci*, 14(2), 481-486.
- Field, J., Waterhouse, P., & German, M. (2010). Quantifying and qualifying surface changes on dental hard tissues in vitro. *J Dent*, 38(3), 182-190.
- Ganss, C., Klimek, J., Brune, V., & Schürmann, A. (2004). Effects of two fluoridation measures on erosion progression in human enamel and dentine in situ. *Caries Res*, 38(6), 561-566.
- Ganss, C., Klimek, J., & Starck, C. (2004). Quantitative analysis of the impact of the organic matrix on the fluoride effect on erosion progression in human dentine using longitudinal microradiography. *Archives of Oral Biology*, 49(11), 931-935.
- Ganss, C., & Lussi, A. (2014). Diagnosis of erosive tooth wear. *Monogr Oral Sci*, 25, 22-31.
- Ganss, C., Schlueter, N., Hardt, M., Schattenberg, P., & Klimek, J. (2008). Effect of fluoride compounds on enamel erosion in vitro: a comparison of amine, sodium and stannous fluoride. *Caries Res*, 42(1), 2-7.
- Hara, A. T., & Zero, D. T. (2008). Analysis of the erosive potential of calcium-containing acidic beverages. *Eur J Oral Sci*, 116(1), 60-65.
- Hove, L. H., Holme, B., Young, A., & Tveit, A. B. (2007). The erosion-inhibiting effect of TiF₄, SnF₂, and NaF solutions on pellicle-covered enamel in vitro. *Acta Odontol Scand*, 65(5), 259-264.
- Hove, L. H., Stenhagen, K. R., Holme, B., & Tveit, A. B. (2014). The protective effect of SnF₂ containing toothpastes and solution on enamel surfaces subjected to erosion and abrasion in situ. *Eur Arch Paediatr Dent*, 15(4), 237-243.
- Hove, L. H., Young, A., & Tveit, A. B. (2007). An in vitro study on the effect of TiF₄ treatment against erosion by hydrochloric acid on pellicle-covered enamel. *Caries Res*, 41(1), 80-84.
- Jiemkim, A., Tharapiwattananon, T., & Songsiripraduboon, S. (2023). Combined use of stannous fluoride-containing mouth rinse and toothpaste prevents enamel erosion in vitro. *Clin Oral Investig*, 27(9), 5189-5201.
- Joshi, M., Joshi, N., Kathariya, R., Angadi, P., & Raikar, S. (2016). Techniques to Evaluate Dental Erosion: A Systematic Review of Literature. *J Clin Diagn Res*, 10(10), Ze01-ze07.
- Jung, K., Kerzel, P., Hara, A. T., Luka, B., Schlueter, N., & Ganss, C. (2025). Hydroxyapatite in Oral Care Products: In vitro Effects on Erosion/Abrasion and Analysis of Formulation Components. *Caries Res*, 59(2), 139-150.
- Karaoulani, K., Dionysopoulos, D., Tolidis, K., Kouros, P., Konstantinidis, A., & Hill, R. (2022). Effect of air-abrasion pretreatment with three bioactive materials on enamel susceptibility to erosion by artificial gastric juice. *Dent Mater*, 38(7), 1218-1231.
- Koch, G. r., & Poulsen, S. (2001). *Pediatric dentistry: a clinical approach*. (1st ed. Munksgaard.
- Linnett, V., & Seow, W. K. (2001). Dental erosion in children: a literature review. *Pediatr Dent*, 23(1), 37-43.
- Lussi, A., & Ganss, C. (2014). *Erosive tooth wear: from diagnosis to therapy*. 2nd revised and extended edition. Karger.

- Lussi, A., Hellwig, E., & Klimek, J. (2012). Fluorides-mode of action and recommendations for use. *Schweiz Monatsschr Zahnmed*, 122(11), 1030-1042.
- O'Toole, S., Mistry, M., Mutahar, M., Moazzez, R., & Bartlett, D. (2015). Sequence of stannous and sodium fluoride solutions to prevent enamel erosion. *J Dent*, 43(12), 1498-1503.
- Pace, F., Pallotta, S., Tonini, M., Vakil, N., & Bianchi Porro, G. (2008). Systematic review: gastro-oesophageal reflux disease and dental lesions. *Aliment Pharmacol Ther*, 27(12), 1179-1186.
- Patel, A., Amaechi, B. T., & Brady III, C. (2015). Prevention and control of dental erosion: gastroesophageal reflux disease management. In *Dental erosion and its clinical management* (pp. 203-224). Cham: Springer International Publishing.
- Poggio, C., Gulino, C., Mirando, M., Colombo, M., & Pietrocola, G. (2017). Protective effect of zinc-hydroxyapatite toothpastes on enamel erosion: An in vitro study. *J Clin Exp Dent*, 9(1), e118-e122.
- Poggio, C., Lombardini, M., Colombo, M., & Bianchi, S. (2010). Impact of two toothpastes on repairing enamel erosion produced by a soft drink: an AFM in vitro study. *J Dent*, 38(11), 868-874.
- Ranjitkar, S., Smales, R. J., & Kaidonis, J. A. (2012). Oral manifestations of gastroesophageal reflux disease. *J Gastroenterol Hepatol*, 27(1), 21-27.
- Scaramucci, T., Carvalho, J. C., Hara, A. T., & Zero, D. T. (2015). Causes of Dental Erosion: Intrinsic Factors. In B. T. Amaechi (Ed.), *Dental Erosion and Its Clinical Management* (pp. 35-67). Springer International Publishing.
- Schlueter, N., Hara, A., Shellis, R. P., & Ganss, C. (2011). Methods for the measurement and characterization of erosion in enamel and dentine. *Caries Res*, 45(Suppl 1), 13-23.
- Schlueter, N., & Luka, B. (2018). Erosive tooth wear-a review on global prevalence and on its prevalence in risk groups. *Br Dent J*, 224(5), 364-370.
- Shellis, R. P., Featherstone, J. D., & Lussi, A. (2014). Understanding the chemistry of dental erosion. *Monogr Oral Sci*, 25, 163-179.
- Shellis, R. P., Ganss, C., Ren, Y., Zero, D. T., & Lussi, A. (2011). Methodology and models in erosion research: discussion and conclusions. *Caries Res*, 45(Suppl 1), 69-77.
- Steiner-Oliveira, C., Nobre-dos-Santos, M., Zero, D. T., Eckert, G., & Hara, A. T. (2010). Effect of a pulsed CO2 laser and fluoride on the prevention of enamel and dentine erosion. *Arch Oral Biol*, 55(2), 127-133.
- Stenhagen, K. R., Hove, L. H., Holme, B., & Tveit, A. B. (2013). The effect of daily fluoride mouth rinsing on enamel erosive/abrasive wear in situ. *Caries Res*, 47(1), 2-8.
- Wiegand, A., & Attin, T. (2011). Design of erosion/abrasion studies--insights and rational concepts. *Caries Res*, 45(Suppl 1), 53-59.
- Yamasaki, T., Hemond, C., Eisa, M., Ganocy, S., & Fass, R. (2018). The Changing Epidemiology of Gastroesophageal Reflux Disease: Are Patients Getting Younger?. *J Neurogastroenterol Motil*, 24(4), 559-569.
- Young, A., & Tenuta, L. M. (2011). Initial erosion models. *Caries Res*, 45(Suppl 1), 33-42.
- Zanatta, R. F., Caneppele, T. M. F., Scaramucci, T., El Dib, R., Maia, L. C., Ferreira, D. M. T. P., & Borges, A. B. (2020). Protective effect of fluorides on erosion and erosion/abrasion in enamel: a systematic review and meta-analysis of randomized in situ trials. *Archives of Oral Biology*, 120, 104945.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.



Copyright: © 2026 by the authors. This is a fully open-access article distributed under the terms of the Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0).