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Original Article

Acid Erosion Potential of ORAPLA Oral Liquid Bandage on Bovine Enamel and Dentin: A Simulated Long-Term Exposure Study

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ABSTRACT

Inflammation of the oral mucosa can result in significant discomfort and disrupt eating habits, thereby diminishing quality of life. Nevertheless, limited self-care treatments are currently available. Oral liquid bandages provide protection by forming a thin film over injured tissues. This study aimed to evaluate the potential risk of acid erosion when a newly formulated oral liquid bandage (ORAPLA) unintentionally comes into contact with teeth and to determine the comparative risk of acid-related erosion at various time intervals corresponding to the upper limit of its continuous-use duration. ORAPLA was applied to enamel and dentin specimens prepared from 45 bovine mandibular anterior teeth, followed by an acid challenge in a simulated oral cavity containing artificial saliva. Each exposure cycle lasted 6 h. Enamel exhibited visible surface defects and a reduction in Vickers hardness after nine cycles, while surface roughness remained unchanged. Dentin samples showed greater parenchymal damage, elevated surface roughness, and a gradual decline in hardness as exposure time increased. No considerable acid corrosion was identified in enamel even after exposure equivalent to nine times the recommended usage limit, nor in dentin after six times that duration. Therefore, the overall acid erosion risk from accidental adherence to tooth surfaces appears minimal, and in a natural human oral environment with salivary buffering and remineralization, it is expected to be even less.

Keywords: Acid erosion, Enamel, Dentin, Liquid bandage, Demineralization, Risk evaluation

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Introduction

Dental acid erosion refers to the chemical dissolution of tooth tissues independent of bacterial activity. Beverages, foods, and medications with pH values below 5.5 may rapidly demineralize enamel, removing calcium and phosphate that constitute hydroxyapatite—the mineral framework of enamel [1]. Dentin exposed due to gingival recession has higher collagen content and a critical pH of 6.0–6.2, making it particularly vulnerable to acidic environments [1]. Erosive effects associated with pharmaceuticals can result from chewing acidic capsules or from accidental retention of acidic ointments or solutions on teeth for extended periods [1]. Since discontinuation of long-term therapeutic medications requires medical supervision and is not typically managed in dental offices, it is important to preemptively clarify the potential for erosion caused by sustained drug exposure.

Stomatitis, an intensely painful inflammatory disorder affecting the oral mucosa, disrupts normal eating, speaking, and daily life [2, 3]. The oral mucosa, constantly exposed to mechanical, thermal, or chemical stress, frequently suffers recurrent injuries in the same region. The two primary clinical forms are aphthous and catarrhal stomatitis [2, 4, 5]. Aphthous stomatitis is characterized by circular or oval ulcers with distinct borders, a necrotic yellow-gray center, and an erythematous periphery suggesting active inflammation [2, 3, 6, 7]. Recurrent aphthous ulcers commonly occur in children, impairing chewing, swallowing, and speech [7, 8]. Catarrhal stomatitis,

which can appear at any age, is generally caused by mechanical irritation. Within dental settings, this form often arises when orthodontic appliances or dentures abrade mucosal surfaces, inducing lesions and inflammation [2, 9]. Other causes include trauma from cheek biting or contact with hot fluids and chemicals, as well as bacterial irritation. This type typically shows diffuse borders, swelling, and symptoms such as burning, halitosis, and reduced taste sensitivity [3, 10]. According to the Japanese Orthodontic Association's "Risks and Side Effects of Orthodontic Treatment," orthodontic devices can initially cause discomfort, mucosal ulcers, and pain due to tooth movement [11]. However, given the rapid epithelial regeneration rate of the oral mucosa (6–12 days), most lesions heal quickly with favorable outcomes, so care for oral mucosal wounds is often underestimated in everyday dental practice.

Inflammation of the oral mucosa is also clinically important in hospitalized or systemically ill patients. Oral mucositis (OM) is a frequent adverse reaction to chemotherapy and radiotherapy [12]. Approximately 40% of individuals undergoing chemotherapy develop OM, and this incidence increases to about 90% among head and neck cancer patients receiving combined therapy [6]. Cancer therapy–related OM typically presents as erythematous, atrophic, or ulcerative lesions [12]. To date, no clinical studies have conclusively verified the efficacy of any particular therapeutic or preventive approach [12]. Stress and psychiatric conditions are closely linked to self-inflicted mucosal injuries, such as morsicatio, which occurs mainly in young females and children [13, 14]. This condition arises from habitual chewing or rubbing of the mucosa due to psychological stress, most often affecting the buccal mucosa, tongue, or lips [13, 14]. In practice, dentists generally manage oral mucosal injuries and stomatitis by minimizing mechanical irritation—through appliance adjustment—and by prescribing dexamethasone ointments. For patients, self-management options are largely confined to maintaining oral hygiene and modifying diet.

Wound dressings and patches act as physical barriers, lowering infection risk, retaining moisture, and promoting tissue repair [15]. These benefits apply not only to cutaneous injuries but also to mucosal epithelium; gingival patches, for example, have been shown to alleviate gingival inflammation [16]. Despite this, products designed specifically as oral liquid bandages remain scarce, highlighting a need for new formulations aimed at mucosal wound care. The oral liquid bandage ORAPLA (FUJIFILM Toyama Chemical Co., Ltd., Tokyo, Japan) is engineered to react with saliva to form a thin, protective film that shields lesions caused by stomatitis, oral mucositis, dentures, or orthodontic appliances. It incorporates a carboxyvinyl polymer (carbomer) as its base—an ingredient long used as a water-soluble thickening agent in both cosmetic and pharmaceutical applications. Given this composition, the possible risk of dental acid erosion from accidental tooth contact or extended exposure requires investigation. The null hypothesis assumed that the acidity of ORAPLA may induce erosion. This research therefore aimed to determine the extent of enamel and dentin erosion risk from ORAPLA deposition on teeth and to compare the results across multiple durations of its maximum continuous-use period against over-the-counter agents known to be safe. Our findings demonstrate that any acid-related dental erosion from incidental contact is minimal and, within the buffering and remineralizing environment of the human mouth, expected to be even less significant.

Materials and Methods

Preparation of enamel and dentin samples

Forty-five bovine lower anterior teeth were sourced from a slaughterhouse and used as experimental material. Each of the five experimental sets contained five specimens (n = 5 per set). After removal of residual gingival tissue and cementum, only the crowns—comprising enamel and dentin—were used. Cubic blocks measuring 1 cm × 1 cm × 1 cm were cut with a precision high-speed saw (HS-45A, HEIWA Technical Co., Ltd., Tokyo, Japan) and subsequently smoothed using waterproof sandpapers of #1000, #2000, and #4000 grit sizes. On the labial surface, a 5 mm × 5 mm exposure window was created using inlay wax to define the test zone. Techniques for Vickers microhardness and 3D laser surface mapping were standardized among operators under professional supervision. Ethical clearance for the animal-derived specimens was obtained from the Institutional Animal Ethics Committee of Tokyo Dental College (Approval No. 230901, dated 1 April 2023). Additional approval was issued by the college's conflict of interest committee (Approval No. 326, dated 31 July 2023).

The test substance, ORAPLA (FUJIFILM Toyama Chemical Co., Ltd., Tokyo, Japan), is intended for commercial release as a general-use medical device (notification No. 13B2X00129000001). Its biological safety profile has been confirmed through a range of independent evaluations, including: cytotoxicity testing (Nos. 410234 and 410241, Mouse L929 cells, 63.7 mg/mL extraction, 7-day in vitro exposure), adjuvant and patch testing (No. 410238, Cavia porcellus Kwl:Hartley, 0.1 g/site for 24 h × 3 primary

applications, 0.2 g/site for 48 h secondary, and 0.02 g/site for 24 h challenge), oral mucosal irritation test (No. 410237, hamster Slc:Syrian, 0.1 g/site, applied hourly for four rounds), and systemic toxicity evaluation (No. 410239, rat Crlj:CD(SD), oral administration of extract suspension at 1835 and 917 mg/kg/day over 28 days).

Acid challenge using circulating artificial saliva

A custom-built system was employed in which dentin and enamel samples coated with ORAPLA were exposed to a continuous flow of artificial saliva to simulate prolonged intraoral contact **(Figure 1)**. The experimental cycle consisted of two parts: (1) a conditioning phase to hydrate and precondition surfaces and (2) an acid exposure phase. During conditioning, uncoated blocks were soaked in artificial saliva at 37 °C for one hour, after which a uniform 50–100 mg layer of ORAPLA was applied over the 5 × 5 mm area. Samples were then transferred to the acid exposure chamber, where they remained under artificial saliva circulation at 37 °C for 6 h. These two steps together constituted one full experimental cycle **(Figure 1)**.

Enamel samples were classified into four treatment groups:

1. no ORAPLA (control);
2. three-cycle exposure (6 h × 3 = 18 h total);
3. six-cycle exposure (6 h × 6 = 36 h total);
4. nine-cycle exposure (6 h × 9 = 54 h total).

Dentin samples were divided into five categories:

1. no ORAPLA (control);
2. two-cycle exposure (6 h × 2 = 12 h total);
3. four-cycle exposure (6 h × 4 = 24 h total);
4. six-cycle exposure (6 h × 6 = 36 h total);
5. A-Corp treatment (6 h × 6 = 36 h total).

The A-Corp group used a commercially available oral ointment formulated for treating mucosal inflammation and stomatitis. Its composition, provided in **Table 1**, includes carboxyvinyl polymer similar to ORAPLA and exhibits mild acidity but has not been associated with enamel erosion or adverse reactions since release. Thus, A-Corp was employed as the reference formulation. Each group contained five samples (n = 5). For paired comparisons on the same block, half of the polished enamel surface was masked with dental inlay wax (Inlay Wax Soft, GC Co., Ltd., Tokyo, Japan).

Artificial saliva for each test cycle was freshly prepared using 0.02 M HEPES buffer (Sigma–Aldrich, St. Louis, MO, USA) containing 3 mM calcium, 1.8 mM phosphate, a pH of 7.3, and a saturation index of 10. The chamber contained 20 mL of this medium per sample, circulated continuously at 0.3 mL/min by a peristaltic pump during both stages. Gentle rotary agitation maintained homogeneity throughout the system.

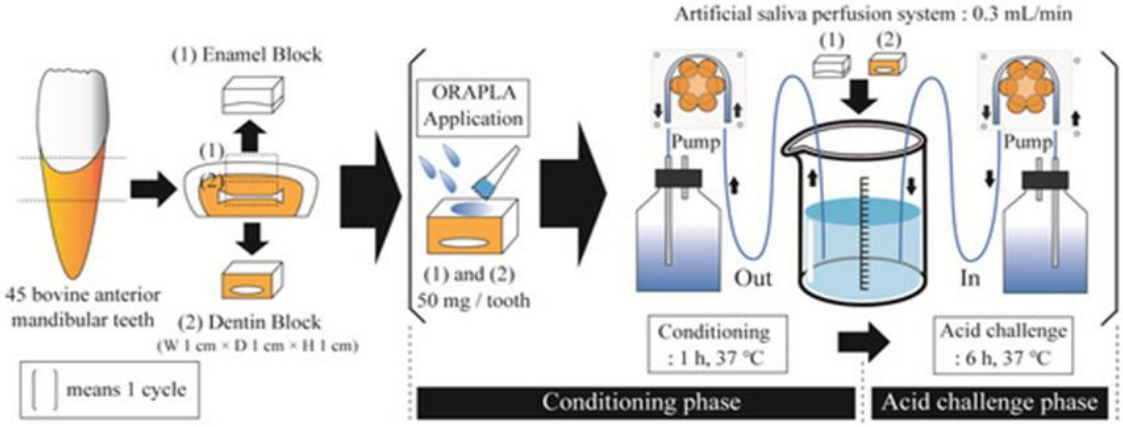


Figure 1. Schematic representation of the acid challenge system. The procedure alternates between conditioning and acid exposure phases, forming one cycle. Artificial saliva is circulated by a peristaltic pump at 0.3 mL/min. Dashed lines indicate sectioning planes of the tooth.

Table 1. The results of quantum-chemical calculations

Product	pH	Amount Used	Composition
ORAPLA (Experimental formulation)	4.67	300 mg	Carboxyvinyl polymer (acidic component), Gelled hydrocarbon, Sodium alginate, Aluminium lactate
A-Corp (Anonymous OTC product)	5.58	300 mg	Carboxyvinyl polymer (acidic component), Gelled hydrocarbon, Xylitol, Hypromellose, L-Menthol

Surface topography via 3D laser microscopy

After removing residual wax, all samples were passed through an ascending ethanol dehydration series. Post-exposure surface alterations were analyzed using a 3D laser microscope (LEXT OLS4000, Olympus, Tokyo, Japan) to measure the height difference between treated (experimental) and protected (reference) regions. The examined area was set to 645 × 645 µm. Images were recorded along the interface separating the acid-affected experimental surface (ES) and the wax-shielded reference surface (RS). For each specimen, five measurement points were analyzed to calculate mean and standard deviation values. This analysis quantified the mean surface roughness of the ES. When constructing the roughness profile, wavelengths above 80 µm were excluded from the section curve. Roughness parameters were obtained from five independent sites per sample positioned along the ES–RS boundary. The number of prominent surface defects and Sa values were documented, and the mean ± SD was computed for every group.

Micro-vickers hardness measurement

After dehydration through an ethanol gradient, each specimen's hardness was evaluated using a Shimadzu HMV-1 tester (Tokyo, Japan). The testing parameters were maintained at a 0.49 N load and 20-second dwell period. To normalize inter-sample variability, the hardness alteration was expressed as ΔHV = RS − ES. Each specimen was indented at five points, and the average and standard deviation were computed for both HV and ΔHV values.

Scanning electron microscopy for cross-sectional and surface analysis

Following acid exposure, samples were rinsed with xylene and passed through ascending ethanol concentrations for dehydration. The surface morphology of the enamel was visualized using a scanning electron microscope (SU6600, HITACHI, Tokyo, Japan) operated at 15 kV. Specimens were then embedded in polyester resin (Rigolac, Nisshin EM, Tokyo, Japan), sectioned, and polished to examine their internal cross-sectional structures.

Statistical evaluation

Results were summarized as mean ± standard deviation, derived from five replicates per condition. Intergroup differences were assessed using one-way ANOVA, and outcomes were regarded as significant when $p < 0.05$. Where ANOVA indicated significance, the Bonferroni correction was employed for multiple comparisons. All analyses and visualizations were completed using ORIGIN 2023 (Lightstone Corp., Tokyo, Japan).

Results and Discussion

Enamel step height after acidic exposure

The three-dimensional surface mapping obtained by 3D laser microscopy **(Figure 2)** displays the height variations between the reference area (RS)—protected with wax—and the exposed site (ES) that underwent prolonged ORAPLA treatment.

The control group exhibited no measurable mineral depletion, with only a minor surface discontinuity of 0.104 ± 0.052 µm. The 3-cycle condition presented slightly greater surface loss (0.186 ± 0.046 µm), though the difference was not statistically meaningful ($p > 0.05$). The 6-cycle samples recorded a loss of 0.161 ± 0.063 µm, which also did not differ significantly from control levels. In contrast, the 9-cycle condition showed the greatest step height (0.241 ± 0.073 µm, $p < 0.05$ vs. control), yet without significant distinction from the 3- or 6-cycle groups.

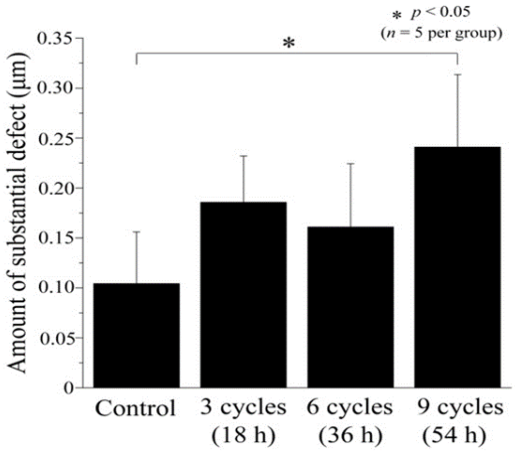


Figure 2. Surface discontinuities on enamel measured by 3D laser microscopy. The vertical distance between RS and ES indicates the degree of demineralization following acid exposure.

Surface roughness (Sa) post acidic challenge: enamel

The groupwise comparison of surface roughness is presented in **Figure 3**. The control samples showed a smooth profile with a mean Sa = 0.125 ± 0.057 µm, a median of 0.105 µm, and an interquartile span from 0.073 to 0.188 µm. The 3-cycle samples produced a mean Sa = 0.215 ± 0.048 µm and median 0.221 µm (0.162–0.265). The 6-cycle specimens had the highest roughness (0.217 ± 0.050 µm, median 0.208 µm (0.166–0.272)). In comparison, the 9-cycle group revealed slightly lower roughness (0.195 ± 0.045 µm, median 0.179 µm (0.152–0.247)). No statistically

significant variation appeared across all tested groups ($p > 0.05$).

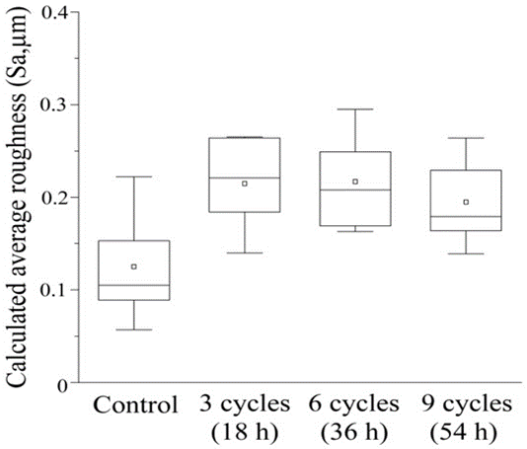
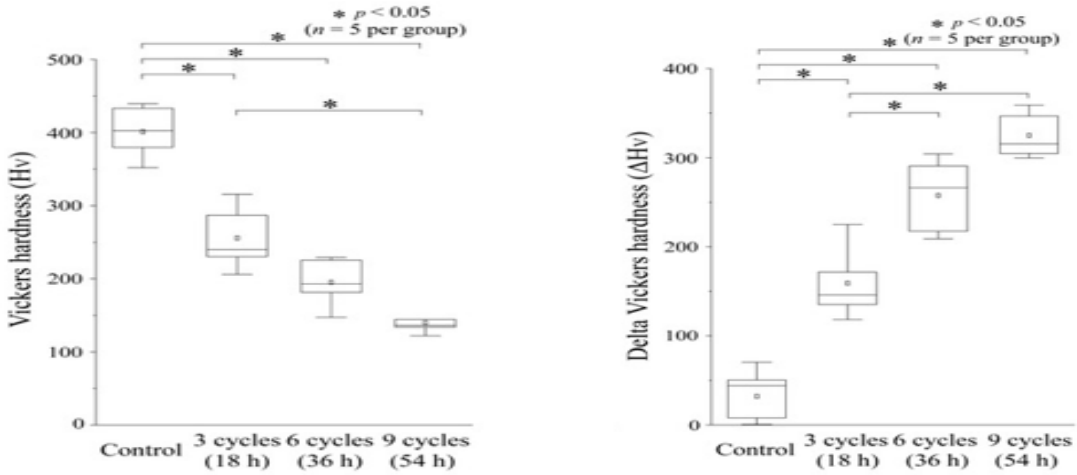


Figure 3. Box plot of enamel surface roughness values. The horizontal line indicates the median, the box limits correspond to the 25th and 75th percentiles, and the white squares denote mean values. Each experimental group consisted of five specimens.

Vickers hardness and its variation after acid challenge: enamel

Vickers hardness results for the experimental surfaces (ES) are shown in **Figure 4a**. The control samples exhibited the highest mean value (401.4 ± 32.72, median 402.4, range 365.9–436.3), differing significantly from all other tested groups ($p < 0.05$). The 3-cycle samples demonstrated a considerable reduction (255.7 ± 39.80, median 240.0, range 218.1–301.2). The 6-cycle condition had an even lower hardness (195.2 ± 30.36, median 193.0, range 164.1–227.5) but was statistically similar to the 3-cycle results ($p > 0.05$). The 9-cycle group exhibited the lowest hardness overall (140.0 ± 13.49, median 136.5, range 128.0–153.7), with a significant difference compared with the 3-cycle samples ($p < 0.05$).



a) b)

Figure 4. (a) Distribution of Vickers hardness (HV) values after acid exposure. (b) ΔHV indicates the hardness difference between RS and ES, computed as ΔHV = RS − ES.

Figure 4b illustrates variations in Vickers hardness, signifying the alteration in surface hardness before and after the acid exposure. The control group demonstrated the smallest shift, recording a mean of 32.14 ± 39.85 and a median of 44.14 (2.015–60.31), whereas all other groups differed significantly ($p < 0.05$). For the 3-cycle group, the hardness change averaged 159.1 ± 37.19, with a median of 145.8 (126.7–198.2), indicating a higher value than the control. The 6-cycle group revealed a notably greater alteration than the 3-cycle group, showing a mean of 257.6 ± 38.25 and median of 266.4 (213.3–297.5) ($p < 0.05$). The 9-cycle group recorded the highest difference, at 325.2 ± 23.61 on average and 315.5 (302.2–353.0) for the median, though the difference between the 6- and 9-cycle groups was not statistically significant.

Step height profiles after acid challenge: dentin

Figure 5 summarizes the 3D laser microscopy data, showing dentin surface contours following acidic exposure. In each image **(Figures 5a–5e)**, the left side (RS)—covered with wax—remained protected, while the right side (ES) underwent demineralization. The control group exhibited nearly no demineralization, with an average defect of 0.104 ± 0.059 µm, and differed significantly from all other groups ($p < 0.01$), **(Figures 5a and 5f)**. The 2-cycle group displayed 7a much greater step height, reaching 2.123 ± 0.553 µm ($p < 0.01$ vs. control; **(Figures 5b and 5f)**). The 4-cycle

group showed a similar elevation (3.302 ± 0.508 µm), without significant variation from the 2-cycle group ($p > 0.05$; **(Figures 5c and 5f)**). The 6-cycle group had the largest defect overall, at 4.256 ± 0.553 µm **(Figures 5d and 5f)**, significantly higher than the 2-cycle group ($p < 0.01$). The A-Corp group showed an average of 3.292 ± 0.595 µm, comparable to the 4-cycle set, and though not different from experimental groups, it exhibited larger defects than the control **(Figures 5e and 5f)**.

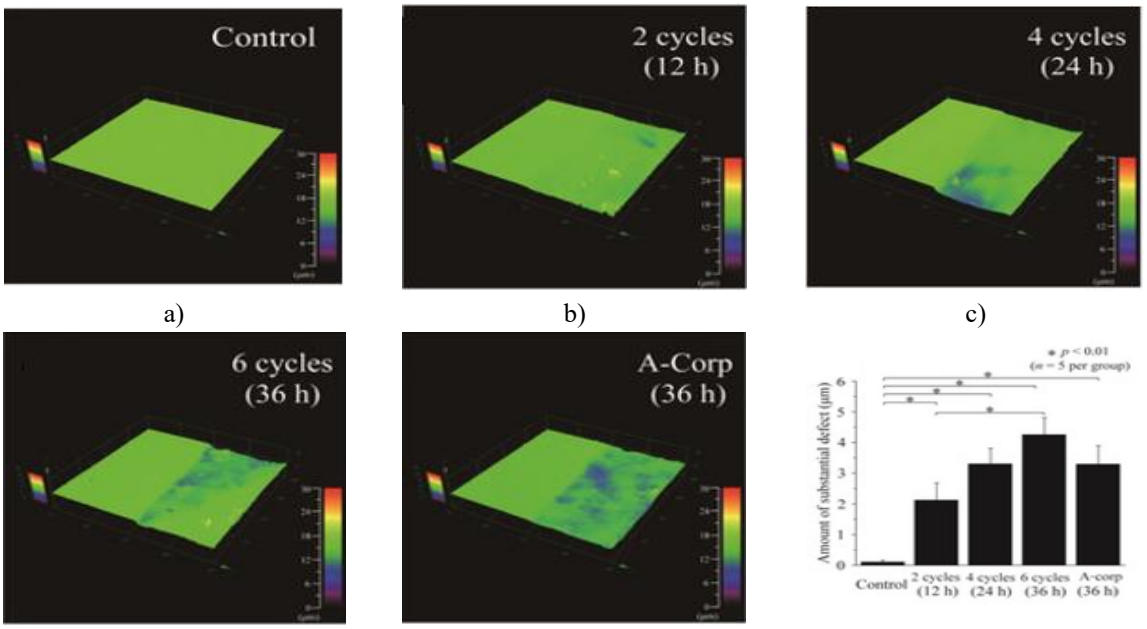


Figure 5. 3D laser microscope assessment of surface step height profiles. Panels (a–e) display RS–ES boundaries for (a) control, (b) 2-cycle, (c) 4-cycle, (d) 6-cycle, and (e) A-Corp specimens. The RS on the left was wax-shielded, while the ES on the right was acid-exposed. Panel (f) quantifies demineralization depth for all groups.

Average roughness after acid challenge: dentin

Figure 6 presents box plots of surface roughness (Sa) across groups. The control displayed minimal roughness (0.105 ± 0.044 µm, median 0.104 µm [0.058–0.152]), and was significantly smoother than all others ($p < 0.01$). In contrast, the 2-cycle group exhibited a mean Sa of 0.289 ± 0.043 µm, median 0.281 µm (0.247–0.335); the 4-cycle group measured 0.325 ± 0.024 µm, median 0.327 µm (0.298–0.352). The 6-cycle group showed the greatest roughness (0.356 ± 0.042 µm, median 0.357 µm [0.318–0.394]). The A-Corp group averaged 0.285 ± 0.029 µm, median 0.296 µm (0.259–0.307), with values significantly higher than the control but not different from experimental groups.

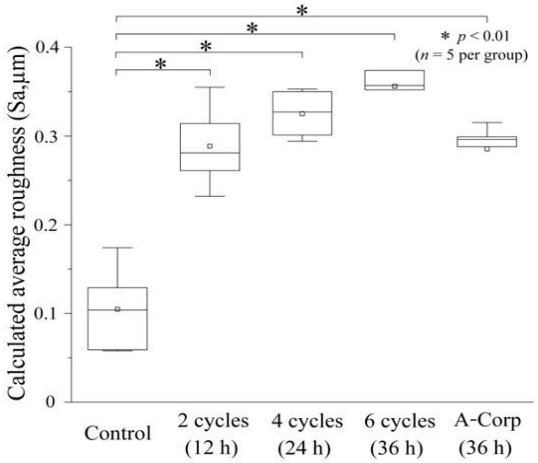
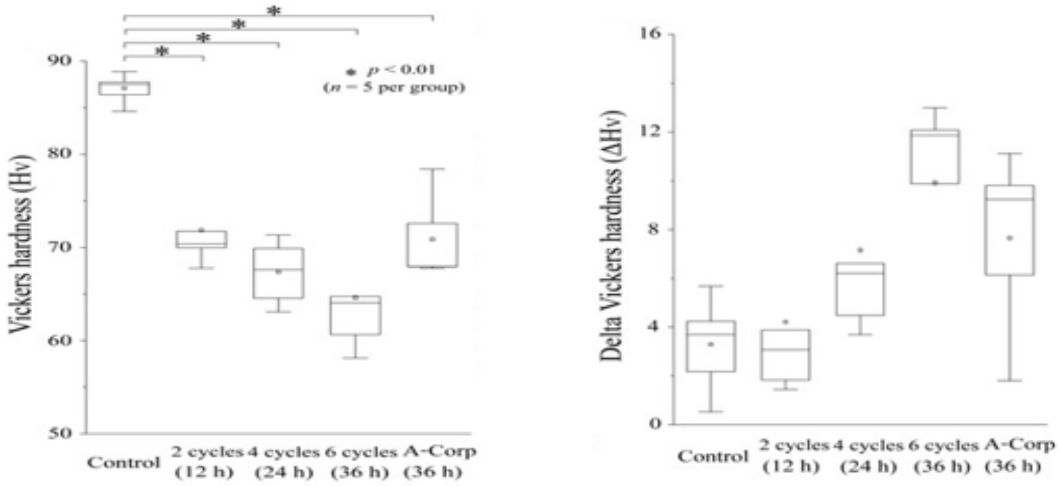


Figure 6. Average roughness (Sa) following acid exposure.

Vickers hardness and its changes after acid challenge: dentin

The **Figure 7a** plot presents Vickers microhardness for each ES. The control group retained the highest hardness (87.03 ± 1.441, median 87.50 [85.51–88.32], $p < 0.01$ vs. others). The 2-cycle group dropped to 71.91 ± 4.113, median 70.38 [68.87–75.73]. Similarly, the 4-cycle group showed 67.29 ± 3.112, median 67.62 [63.82–70.62], aligning with the 2-cycle group. The 6-

cycle group reached the lowest mean (64.61 ± 5.940, median 64.06 [59.38–70.12]). The A-Corp group recorded 70.93 ± 4.16, median 67.95 [67.86–75.50], showing no notable difference from the 6-cycle group ($p > 0.05$).



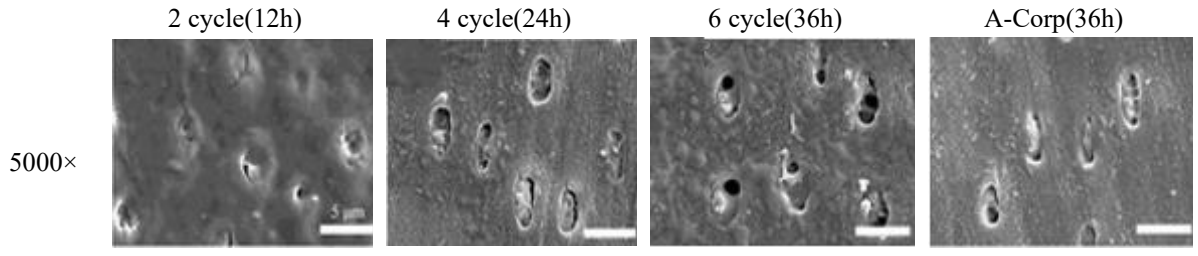
a) b)

Figure 7. (a) Vickers hardness (HV) for each condition (n = 5; *, $p < 0.01$); (b) ΔHV (difference between RS and ES hardness) (n = 5).

Figure 7b shows the hardness variation (ΔHV) before and after acid exposure. The control exhibited the smallest change (3.261 ± 1.770, median 3.690 [1.348–4.960]). The 2-cycle group followed with 4.182 ± 3.367, median 3.066 [1.635–7.286]. The 4-cycle group rose to 7.135 ± 3.926, median 6.206 [4.087–10.65], exceeding the control. The 6-cycle group displayed the most substantial variation (9.896 ± 3.753, median 11.86 [6.275–12.53]). Finally, the A-Corp group registered 7.620 ± 3.337, median 9.240 [3.970–10.46], with no statistical difference from other test groups ($p > 0.05$).

Surface SEM analysis after acid exposure: dentin

Figure 8 presents secondary electron micrographs showing the dentin surface morphology following the acid exposure test. The 2-cycle specimens exhibited a relatively even and polished surface without notable etching or acid-related deterioration. Most dentinal tubules appeared occluded, and those that were open displayed narrow lumens **(Figures 8a and 8e)**. In the 4-cycle specimens, minor surface irregularities attributable to acid contact were seen, and slight roughness appeared around some tubule margins. Although the majority of tubules remained closed, their number of open lumens was greater than that in the 2-cycle samples **(Figures 8b and 8f)**. The 6-cycle group revealed modest surface irregularities caused by acid interaction, with peritubular areas showing increased surface texture compared with the 4-cycle condition **(Figures 8c and 8g)**. Roughly 50–60% of the tubules were closed, and the number of open tubules surpassed that observed in the 4-cycle group. Even where openings were present, approximately 60–80% of their cross-sectional area remained occluded **(Figures 8c and 8g)**. The A-Corp group showed a surface appearance similar to that of the 4-cycle group, with slight irregularities and localized etching. Roughly 60–70% of tubules were closed, and the proportion of open tubules was comparable to the 4-cycle samples. Tubular openings were typically small, with 60–80% occlusion of the lumen cross-section **(Figures 8d and 8h)**.



a) b) c) d)

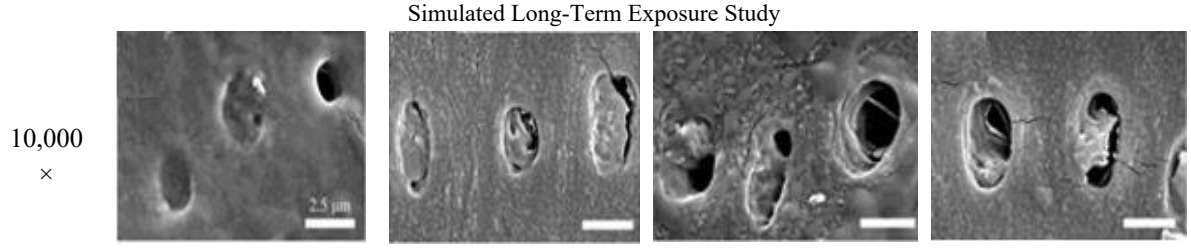


Figure 8. Scanning electron microscopy (SEM) micrographs showing dentin surface features post–acid challenge. Images correspond to 2-cycle (a,e), 4-cycle (b,f), 6-cycle (c,g), and A-Corp (d,h) specimens. Panels (a–d) show 5 µm scale bars at 5000× magnification after Au–Pd coating; panels (e–h) show 2.5 µm scale bars at 10,000× magnification following Au–Pd coating.

Cross-sectional SEM analysis after acid exposure: dentin

Figure 9 illustrates reflected electron images of cross-sectioned ES surfaces post–acid exposure. The 2-cycle samples displayed no lateral widening of tubule orifices and no apparent increase in tubule depth. Furthermore, there was an absence of demineralization related to calcium dissolution by acid **(Figures 9a and 9e)**. The 4-cycle samples, much like the 2-cycle ones, exhibited no tubule broadening or deepening, and no signs of dentin mineral loss were visible; however, some tubules presented mild funnel-shaped expansion near the opening **(Figures 9b and 9f)**. The 6-cycle samples showed a similar microstructure to the 4-cycle specimens, with no evident acid-induced deterioration or tubule alteration **(Figures 9c and 9g)**. The A-Corp samples displayed no visible distinctions compared to the 6-cycle group **(Figures 9g and 9h)**.

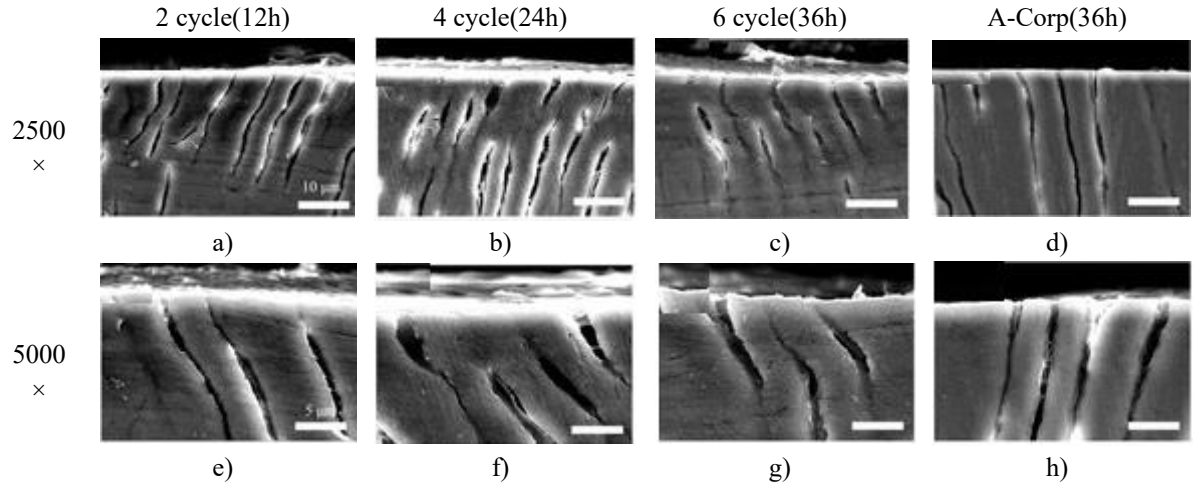


Figure 9. SEM micrographs of dentin cross sections following the acid challenge. Shown are 2-cycle (a,e), 4-cycle (b,f), 6-cycle (c,g), and A-Corp (d,h) specimens. Panels (a–d): 10 µm scale bars at 2500× magnification. Panels (e–h): 5 µm scale bars at 5000× magnification. All micrographs were taken following carbon evaporation coating.

Evaluation of enamel erosion risk

Extended enamel contact with ORAPLA for up to six cycles (36 h) resulted in no major substance loss, and Vickers hardness values remained within the physiological limits of normal enamel, indicating minimal erosive impact. The control group served as a model for neighboring teeth unaffected by direct ORAPLA placement (3-, 6-, and 9-cycle groups). Control specimens were kept in the same environment and artificial saliva for 54 h—the longest exposure period—and thus experienced potential influence from dissolved ORAPLA components. No measurable erosion, surface defects, or hardness reduction occurred in this control condition **(Figures 2-4)**.

These findings confirm that under typical intraoral circumstances, ORAPLA use does not induce acid erosion on enamel, even with extended contact. The 3-cycle group, where enamel surfaces were directly coated, showed results indistinguishable from the control regarding surface morphology, roughness, and Vickers hardness—all values remaining within healthy enamel ranges **(Figures 2–4)**. The typical hardness of sound enamel lies between 270–366 HV [17], and the 3-cycle mean was comparable to this range **(Figure 4a)**.

For the 6-cycle group, although surface roughness and defect size did not significantly differ from controls, the Vickers hardness declined below normal enamel levels **(Figures 2–4)**, suggesting minor acid effects on the subsurface structure **(Figure 4a)**. This trend was also evident in ΔHV, which increased with exposure time and showed statistical significance between the 3- and 6-cycle groups **(Figure 4b)**. In the 9-cycle condition (54 h exposure), surface roughness remained stable, but small structural defects and a modest hardness reduction were detected, reflecting mild acidic degradation of the enamel **(Figures 2–4)**.

Previously, the extent of enamel surface loss observed after 60 minutes of contact with acidic beverages was estimated using the following equation:

Enamel loss (μm) = 6.676 − 1.726 pH + 0.233 TA (titratable acidity) [18, 19].

A commercial cola drink used in deriving this model caused an average surface reduction of 3.05 ± 0.74 μm [18, 19]. A separate confocal laser scanning microscopy analysis reported 5–10 μm enamel defects after 60 minutes of immersion in various beverages (pH 2.42–3.46) [19].

These prior experiments, however, differ from the present study since no artificial saliva was incorporated in their systems.

In contrast, even after 54 hours of cumulative exposure, the 9-cycle group in our research exhibited only 0.241 ± 0.073 μm of enamel loss—the highest recorded here—indicating that ORAPLA induced considerably less damage than standard carbonated beverages.

In everyday conditions, dietary acids from food and drinks are viewed as stronger contributors to erosion than medications or clinical treatments [20–22].

A cohort investigation of 1,753 children demonstrated a positive correlation between fruit juice intake (odds ratio [OR] = 1.42) or carbonated beverage consumption (OR = 1.59–2.52) and the incidence of acid-related erosion post-medical exposure [20–22].

According to ORAPLA's product information, its maximum continuous application period is 6 hours—a duration that defined our experimental cycle intervals, each being a 6-hour multiple.

In actual oral conditions, ORAPLA is unlikely to adhere longer than 6 hours, due to mechanical abrasion and salivary flow from swallowing, eating, or speaking.

Moreover, saliva has a strong carbonic acid buffering ability and supports remineralization of early lesions [23–25].

Even after 36 hours (6 cycles of 6 hours), corresponding to sixfold the normal limit, no major surface loss occurred, and internal enamel disruption remained minimal.

Only at 54 hours (ninefold the usual period) did we observe tiny surface defects.

Nevertheless, given saliva's buffering and remineralizing capacity, accidental ORAPLA retention on enamel surfaces is unlikely to cause measurable erosion.

Assessment of dentin erosion risk

Compared to enamel, dentin has greater collagen content and a higher critical pH (6.0–6.2 versus 5.5), which makes it inherently more vulnerable to acid impact [26, 27].

For dentin, the extent of structural damage, surface irregularity, and Vickers hardness all tended to decline as ORAPLA exposure lengthened **(Figures 5–7)**.

Yet, none of these metrics showed a significant difference from the control A-Corp group after the maximum 36-hour exposure.

In the control samples, no surface defects, no roughness increase, and no hardness loss were detected, even under the same simulated oral system as the test groups (2-, 4-, and 6-cycle) **(Figures 5–7)**.

This indicates that, within normal application limits confined to mucosal contact, dentin is unlikely to experience acidic degradation, even with extended continuous exposure.

The 2-cycle samples exhibited mild surface irregularities and slight defects versus controls, but hardness values still fell within normal dentin parameters [17].

No significant deviation in Vickers hardness was noted, and SEM imaging revealed no enlargement or deterioration of dentin tubule openings **(Figure 7b)**.

The 4-cycle and 6-cycle specimens displayed a gradual rise in surface roughness and defect count with longer exposure, but again, no statistical significance was observed **(Figure 7)**.

SEM surface and cross-sectional images showed localized funnel-shaped openings in a few tubules, whereas most remained closed—suggesting that acid erosion and dentin hypersensitivity were improbable **(Figures 8 and 9)**.

A-Corp, a widely used medication without safety concerns, served as a control reference.

There were no measurable differences between the 6-cycle ORAPLA and A-Corp groups for any parameter, indicating comparable erosion resistance.

The A-Corp samples displayed minor defects and roughness changes similar to those of the 2-cycle and 4-cycle ORAPLA specimens **(Figures 5–7)**.

Therefore, combining cariological, histological, and mechanical evidence, we infer that up to 36 hours of continuous ORAPLA exposure carries a low risk of

dentinal erosion, matching that of standard over-the-counter formulations.

SEM analysis after 36 hours revealed only minimal widening of dentin tubules, implying that sensitivity symptoms are unlikely to occur in real-world application.

Study limitations and applicability to the oral environment

(1) This investigation was conducted in vitro, meaning that it differs from the natural human oral cavity.

We used artificial saliva, stirrers, and fluid flow to mimic intraoral conditions.

The artificial saliva simulated basic buffering and mineral saturation with calcium and phosphorus but lacked proteins, pellicle layers, and oral microbiota [28].

It was based on HEPES buffer, prepared following an established method [29].

HEPES, with a pKa of 7.55 and a pH range of 6.8–8.2, is often applied in biochemical assays, including cell and tissue culture [29].

By contrast, human saliva relies on the carbonic acid–bicarbonate system, which provides 85–95% of total buffering capacity [23–25, 30].

Thus, mineral loss in the mouth is likely more effectively inhibited than in this laboratory setup.

Moreover, stimulated saliva—produced during eating—has stronger buffering capacity than resting saliva, due to higher secretion volume [23-25, 30].

Consequently, demineralization while ORAPLA is present during eating or snacking would likely be further reduced.

(2) Physical interactions within the mouth, such as chewing, swallowing, drinking, and vibrations of the cheeks during speech, are expected to diminish the adhesion and overall impact of ORAPLA on dental surfaces.

In this experiment, the 6-hour exposure period per cycle was chosen under the assumption that the product would be reapplied after each of three meals within an 18-hour waking period, excluding sleeping time.

Nevertheless, in practice, the hydration and mechanical agitation of the gel-like ORAPLA layer are likely to shorten its actual persistence on teeth in vivo.

(3) A major distinction between the artificial saliva used here and natural human saliva concerns the presence of fluoride, which plays an essential role in demineralization resistance.

Exposure to elevated fluoride levels can reduce dentin acid erosion by about 50% or more [31–33].

More than 90% of modern toothpastes include fluoride as an active ingredient, and both children and adults encounter concentrations between 500–1500 ppm multiple times daily through oral hygiene practices [34–36].

Although fluoride incorporation was not simulated in this experiment because bovine teeth were used, human teeth typically contain around 1800 ppm of fluoride at the surface, providing strong protection against mineral loss [37].

Human salivary fluoride normally ranges from 0.05–0.25 ppm, but rises to 1–3 ppm immediately after brushing with a fluoride toothpaste [36, 38].

Within saliva, fluoride ions react with calcium to form calcium fluoride deposits on enamel and dentin, enhancing acid resistance and reducing demineralization [32, 34, 36].

Previous findings suggest that brushing with a fluoride dentifrice prior to consuming acidic foods or drinks helps mitigate erosion [32, 34, 36].

Therefore, in real oral conditions where fluoride is regularly introduced, the erosion potential of ORAPLA would be lower than the levels observed in this in vitro model.

The carboxyl vinyl polymer component in ORAPLA produces only trace amounts of acid, and the neutralization reaction occurs quickly, limiting any sustained acidity within the mouth.

Moreover, while this study used ample product to fully cover the exposed window area on each tooth, in the oral environment only small quantities transfer from mucosal tissues to teeth since direct contact is partial.

Given the fluoride presence in human saliva and the calcium-supersaturated conditions of the mouth, the likelihood of minor acid levels dissolving calcium fluoride and causing noticeable demineralization is minimal.

(4) Another unaccounted factor influencing retention time and potential mineral loss under the liquid bandage is variation in salivary flow among individuals.

Typical secretion rates are approximately 0.3 mL/min for resting saliva and 1.5–2.0 mL/min for stimulated saliva, though significant person-to-person differences exist [23–25].

Reduced salivary output can result from many medications, leading to dry mouth and oral mucositis (OM) in patients with polypharmacy, hypertension, diabetes, or advanced age [25, 39, 40].

In this study, the artificial saliva reflected general composition and saturation values and did not model xerostomia.

When salivary flow is impaired, both buffering efficiency and mechanical clearance of ORAPLA decline, heightening the risk of acid erosion [41].

How secretion rate affects the duration of liquid bandage retention in the mouth remains uncertain and requires future evaluation.

(5) The experimental model also lacked realistic tooth anatomy.

In natural conditions, salivary clearance is greater on smooth tooth surfaces but much less effective in interdental and adjacent regions [42].

Consequently, localized erosion risks may differ between surfaces where the gelatinized bandage adheres longer and those where it is more rapidly washed away.

(6) The control specimens served as negative controls in this study, meaning that the liquid bandage was absent and samples were immersed only in artificial saliva, eliminating any acidic demineralization.

Although the possibility of a positive control was considered, no existing research documents acid erosion caused by oral liquid bandages, and suitable references were unavailable.

Common acidic agents such as lactic acid or hydrochloric acid, frequently used in erosion studies, were deliberately avoided since their viscosity and dynamic behavior differ substantially from that of liquid bandages.

Future research directions

Further in vivo and in vitro analyses should be carried out using human oral models to clarify how individual biological variation affects the acidic impact of ORAPLA.

Because salivary protein-derived pellicles naturally form protective layers on teeth and resist acid attack, future experimental systems should incorporate these pellicular barriers for greater realism.

4.5. Clinical Implications and Advantages of Oral Liquid Bandages

For many dental patients, pain alleviation after treatment is a higher priority than addressing the underlying pathology, and the application of oral liquid bandages may notably enhance quality of life.

In investigations linking denture stomatitis, traumatic ulcers, and variables such as age, gender, education, smoking, denture age, and cleaning habits, approximately 35.8% of participants presented stomatitis, while 29% exhibited traumatic ulcers [43].

Reports estimate that 15–70% of denture users develop stomatitis, often linked to ill-fitting prostheses and repeated mucosal trauma [8].

In dental practice, Vaseline (CAS:8009-03-8, FUJIFILM Wako, Tokyo, Japan) or Cocoa Butter (GC Dental Corp., Tokyo, Japan) is commonly applied to angular cheilitis or oral wounds to relieve pain during mouth movement and to shield affected areas.

However, Vaseline offers only short-term protection.

Given the scarcity of adhesive oral dressings specifically designed for mucosal use, the clinical demand for liquid bandages is likely substantial.

The present findings show that within the recommended ORAPLA usage duration, the risk of acid erosion to enamel and dentin remains very low.

Additionally, consistent professional maintenance—including mechanical cleaning and topical fluoride therapy—combined with daily home care using fluoride toothpaste, can further reduce this risk.

In cases of insufficient self-care, shortened recall intervals for preventive checkups are advised.

Conditions such as oral mucositis or biting injuries should be managed by dental professionals, as ORAPLA is intended strictly for self-care after clinical evaluation.

Conclusion

The potential for acid-induced erosion from ORAPLA was determined to be minimal, with no measurable enamel corrosion even after nine times the manufacturer's 6-hour limit, and no dentin degradation after six times that period.

Comparison with a reference formulation lacking safety concerns revealed no statistically significant differences across all evaluation parameters.

Therefore, the acid erosion hazard from unintentional ORAPLA contact with teeth is low, and would likely be even less pronounced in the human oral environment, where salivary buffering and remineralization processes are active.

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