Research Square

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A Randomized Open-Label Prospective Study of Remineralizing Therapy for Dental Caries in School-Aged Children

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Abstract

Initial carious lesions of permanent teeth in children often develop without pronounced clinical signs, necessitating the use of objective quantitative methods for diagnosis and monitoring of remineralizing therapy.

Objective. To evaluate the effectiveness of fluoride-, calcium-, and arginine-containing products in the remineralizing treatment of initial caries of permanent teeth in school-aged children using quantitative light-induced fluorescence (QLF) and the enamel resistance test (ERT).

Materials and Methods. An open-label prospective clinical study was conducted in 658 children aged 7–15 years, divided into five age groups. The condition of the hard tissues of permanent teeth was assessed by visual-tactile examination, the ERT, and QLF technology, with recording of ΔF max, ΔF average, ΔQ, White Spot Area, White Spot ΔR, White Spot ΔR max, and White Spot ΔR area. Measurements were obtained before and after a course of remineralizing therapy. Statistical analysis included parametric and nonparametric methods; differences were considered significant at $p < 0.05$.

Results. QLF detected significantly more initial foci of demineralization than visual-tactile examination and the ERT. The mean ERT value was 23.31 ± 4.35% in children with a high mineralization level and 56.35 ± 5.34% in those with a low mineralization level. The corresponding ΔF average values were − 8.11 ± 0.67% and − 22.34 ± 0.84%; the between-group differences were highly significant ($p < 0.0001$). After remineralizing therapy, all age groups showed statistically significant improvements in ΔF max, ΔF average, ΔQ, White Spot Area, and White Spot ΔR, together with lower ERT values ($p < 0.05$).

Conclusion. Products containing fluoride, calcium, and arginine promote restoration of mineral density and increase the acid resistance of permanent tooth enamel in children. The combined use of QLF and the ERT enables timely diagnosis of initial demineralization, quantitative assessment of its severity, and objective monitoring of the effectiveness of remineralizing therapy.

Background

According to the World Health Organization (WHO) [1], the prevalence of caries in primary and permanent teeth among children reaches 80–90% in a number of countries, demonstrating the scale and global nature of the problem. The high incidence of this disease has a substantial impact on a child's oral health, general somatic condition, psycho-emotional development, and overall quality of life.

According to current epidemiological and clinical studies [2–4], more than 530 million children worldwide have untreated caries in recently erupted teeth, and disease prevalence increases with age. Thus, structural enamel damage, even during the period of enamel formation, is irreversible and is generally associated with increased susceptibility to external factors. The principal etiological determinants of dental caries are considered to be the combined effects of microbial factors, carbohydrate intake, the condition of the dental hard tissues, and the duration of their interaction,

consistent with the contemporary biofilm-mediated multifactorial model of caries development [2, 3, 5]. Demineralization of dental hard tissues is a complex process caused by acid-producing bacteria in the oral microenvironment in the presence of a substrate. Because the enamel surface is in close contact with saliva and dental plaque, dental hard tissues exhibit a dynamic equilibrium between demineralization and remineralization; these processes are mutually reversible and alternate cyclically depending on local oral conditions. Up to 99% of demineralization occurs during the first year after tooth eruption, and up to 71% is localized on the occlusal surface. Acid attacks by oral biofilms dissolve hydroxyapatite crystals into Ca^{2+} and PO_4^{3-} ions and clinically lead to the first stage of caries, termed a white spot lesion (WSL) [6, 7], which is characterized by enamel demineralization without cavitation. Exposure to an acidic agent and migration of hydrogen ions into the subsurface enamel layer produce funnel-shaped defects and characteristic qualitative color-textural and quantitative changes in enamel microrelief and microstructure, including an increase in the area of destructive regions located 200–400 nm or more below the calculated zero level—“depressions” and “indentations.” Numerous factors play an important role, including buffer systems, the duration of the acid attack, the initial mineralization level (IML), and enamel resistance and susceptibility. Demineralization is characterized by changes in composition and component ratios: the Ca/P molar ratio changes; phosphate-ion and lipid contents decrease; fluoride, certain peptide fractions, and carbohydrates increase; the proportion of disordered phosphate is high; B-type phosphate decreases sharply; and the mineral-to-organic-matrix ratio changes.

The enamel resistance test (ERT), proposed by V.R. Okushko and colleagues in 1984 [8], is based on controlled acid etching of the enamel surface, subsequent staining with methylene blue, and visual assessment of staining intensity using a graded scale. This procedure evaluates enamel acid resistance, which correlates with the degree of mineralization.

Quantitative light-induced fluorescence (QLF) is used for quantitative assessment of dental hard tissues and early detection of initial caries [9–13]. Healthy enamel without signs of demineralization reflects light, whereas damaged (demineralized) hard tissues scatter it because microdefects develop within demineralized areas. Light propagates faster through healthy dental tissues than through carious tissues, allowing optical emission parameters to be used to estimate mineral loss. QLF measurements use blue-violet light with wavelengths of 370–455 nm, which induces fluorescence when it reaches dental hard tissues. Orange-red fluorescence is generated by porphyrins, metabolic by-products of oral bacteria within the dental biofilm [14, 15].

When quantitative light-induced fluorescence values are processed using Inspektor software, the following parameters are calculated: ΔF, ΔF max, ΔF area, ΔQ, White Spot Area, White Spot ΔR, White Spot ΔR max, and White Spot ΔR area. In vitro and in vivo studies of oral biofilm have demonstrated a correlation between red fluorescence recorded by QLF-D, dental biofilm maturity, and caries risk [14–16]. Fluorescence intensity decreases in areas of demineralization. An optical camera and software convert the reflected fluorescent waves into an image displayed on a monitor. Several devices operate on the QLF principle, including the VistaCam IX intraoral camera with interchangeable tips, Spectra, SOPRO LIFE USBM2, and several generations of the Q-ray Cam and Q-ray Pen. QLF devices support both qualitative

diagnosis and assessment of the effectiveness or ineffectiveness of remineralizing therapy. The use of QLF devices with Q-Ray™ software makes it possible to diagnose early carious lesions, monitor the effectiveness of preventive therapy, and modify treatment promptly when necessary. Quantitative light-induced fluorescence is one of the most promising contemporary device-based methods for the early diagnosis and longitudinal monitoring of initial caries [9–13, 17]. The most advanced devices are considered to be the Korean-manufactured Q-ray Cam and Q-ray Pen systems with Q-Ray™ software from Inspektor Research Systems BV, which provide the White Spot Analysis and Simple Hygiene Score analysis modes.

Modern preventive dentistry is based on the principles of minimally invasive dentistry (MID) [3, 18, 19, 32, 35, 37] and etiologic and pathogenetic caries management with early diagnosis, enabling prevention or treatment of carious processes at the earliest stages.

Numerous studies and systematic reviews demonstrate the effectiveness of remineralization for the management of noncavitated carious lesions [20–25, 31]. The approach replenishes mineral components lost from dental hard tissues through the use of remineralizing agents, including fluorides, calcium-phosphate systems, and arginine [20–27]. The principal criterion for the applicability of remineralization is preservation of the integrity of enamel protein structures.

Recent evidence from 2024–2026 has expanded the evidence base for noninvasive cariology. An updated 2024 systematic review and meta-analysis confirmed clinical evidence of the caries-preventive potential of hydroxyapatite-containing products while emphasizing heterogeneity in the designs and results of the included studies [31]. Digital methods for objective assessment of early lesions are also developing, including acoustic screening and artificial-intelligence algorithms for dental image analysis [32, 35, 37]. These approaches do not yet replace clinical examination and QLF, but they reinforce the importance of quantitative longitudinal monitoring of noncavitated carious lesions.

The objective of the study was to evaluate the use of toothpastes containing fluoride, calcium, and arginine for reducing the increment of dental caries in school-aged children, as assessed by quantitative light-induced fluorescence (QLF).

Materials and Methods

To achieve the study objective, a clinical dental examination was performed in 658 children aged 7–15 years residing in Tashkent and the Tashkent Region. Participants were selected by random sampling within a prospective cohort study design. The additional diagnostic method was selected to improve the detection of initial enamel caries, because such lesions cannot always be identified using the visual-tactile diagnostic method recommended by the WHO. The study was approved by the Ethics Committee of Tashkent State Medical University (Resolution No. 341-S22097511 dated 5 March 2026).

The study was conducted at the Department of Simulation-Based Education, Clinical Modeling, and Pediatric Dentistry of Tashkent State Medical University in accordance with the World Medical

Association Declaration of Helsinki [30], “Ethical Principles for Medical Research Involving Human Subjects.” The study population comprised children aged 7–15 years whose legal representatives provided voluntary written informed consent for participation and for the scientific use of the data obtained.

Fig. 1. Overview of alkali-generating pathways in the oral cavity

The localization of carious lesions was recorded using the visual-tactile method (WHO), the Silness–Löe method, and QLF with Q-ray Pen and Q-ray Cam devices and Inspektor Research Systems BV software. QLF does not allow carious lesions on approximal surfaces to be assessed. To determine the frequency of carious lesions according to localization, 1,367 teeth were examined, including 400 premolars and molars. In the group of 7-year-old children, 43 teeth were at different stages of eruption, preventing a complete assessment of all surfaces. Therefore, 414 buccal, oral, mesial, and distal surfaces each were examined (1,656 surfaces in total), together with 177 occlusal surfaces of molars and premolars. In the group of 15-year-old children, clinical examination included 1,324 teeth, of which 804 were molars and premolars; 1,324 buccal, oral, mesial, and distal surfaces each were recorded (5,296 surfaces in total), together with 718 occlusal surfaces of molars and premolars.

To record the presence of a carious lesion by quantitative light-induced fluorescence, the White Spot Analysis software mode was used. The maximum mineral loss parameter, ΔF max, was recorded; it represents the greatest measured ΔF value within the lesion contour.

The examined participants were divided into the following groups: Group 1, aged 7–8 years—130 children (390 teeth); Group 2, aged 9–10 years—130 children (390 teeth); Group 3, aged 11–12 years—132 children (396 teeth); Group 4, aged 13–14 years—132 children (396 teeth); and Group 5, aged 14–15 years—134 children (402 teeth). The data are presented in Table 1.

Table 1. Number of examined children in the different age groups.

Tooth	7–8 years	9–10 years	11–12 years	13–14 years	14–15 years
1.6	8	8	12	13	16
2.6	9	10	11	12	18
3.6	10	12	9	9	12
4.6	11	23	6	4	14
1.4	7	7	5	7	6
1.5	8	8	4	6	5
2.4	6	9	1	10	2
2.5	5	11	7	11	12
3.4	8	12	8	9	7
3.5	7	5	10	10	10
4.4	9	3	11	7	4
4.5	5	2	12	7	6
1.7	7	5	8	6	4
2.7	10	6	7	4	6
3.7	11	4	12	10	7
4.7	9	5	9	7	5

When the presence of carious lesions was recorded using quantitative light-induced fluorescence, the White Spot Analysis and Simple Hygiene Score modes were used, together with the following parameters: ΔF max, ΔF average, ΔQ, White Spot Area, White Spot ΔR, White Spot ΔR max, and White Spot ΔR area.

To assess the potential of a calcium-, fluoride-, and arginine-containing gel for remineralizing therapy at different stages of the carious process, QLF was used during remineralizing treatment with Colgate Maximum Cavity Protection.

Statistical analysis was performed using GraphPad Prism 8.0. Both parametric and nonparametric statistical methods were applied. In the jitter plots and the text, data are presented as medians with interquartile ranges (Me, Q1–Q3). Independent and paired groups were compared using the Mann–Whitney test or the Kruskal–Wallis test followed by Dunn's post hoc test, and the Wilcoxon test, respectively. Pairwise comparisons were performed using the Mann–Whitney U test with the Holm–Bonferroni correction for multiple comparisons. Differences were considered statistically significant at an adjusted $p < 0.05$.

Study Results

During WHO-based clinical examination of 7-year-old children, carious lesions were recorded on the buccal surface in 2 cases, representing 0.5% of all examined surfaces. The ERT identified 15 carious lesions (3.6%). Quantitative light-induced fluorescence detected 100 carious lesions (24.2%). The three diagnostic methods showed highly significant pairwise differences: p1–2 = 0.003; p1–3 < 0.001; p2–3 < 0.001; p1–3 < 0.001.

In the group of 8-year-old children, visual-tactile examination of the buccal tooth surfaces detected no carious lesions (0%). The ERT identified 33 carious lesions, representing 25%. QLF diagnosed 173 carious lesions, or 13.2%. The three diagnostic methods showed highly significant pairwise differences: p1–2 = 0.001; p1–3 < 0.001; p2–3 < 0.001; p1–3 < 0.001.

In the group of 9-year-old children, visual-tactile examination of the buccal tooth surfaces recorded carious lesions in 6 cases, representing 1.2% of all examined surfaces. The ERT identified 27 carious lesions, representing 21%. QLF diagnosed 184 carious lesions, or 15.6%. The three diagnostic methods showed highly significant pairwise differences: p1–2 = 0.003; p1–3 < 0.001; p2–3 < 0.001; p1–3 < 0.001.

In the group of 10-year-old children, visual-tactile examination of the buccal tooth surfaces recorded carious lesions in 4 cases, representing 0.9% of all examined surfaces. The ERT identified 24 carious lesions, representing 19%. QLF diagnosed 169 carious lesions, or 13.9%. The three diagnostic methods showed highly significant pairwise differences: p1–2 = 0.002; p1–3 < 0.001; p2–3 < 0.001; p1–3 < 0.001.

In the group of 11-year-old children, visual-tactile examination of the buccal tooth surfaces recorded carious lesions in 6 cases, representing 1.2% of all examined surfaces. The ERT identified 28 carious lesions, representing 21.5%. QLF diagnosed 171 carious lesions, or 14.1%. The three diagnostic methods showed highly significant pairwise differences: p1–2 = 0.003; p1–3 < 0.001; p2–3 < 0.001; p1–3 < 0.001.

In the group of 12-year-old children, visual-tactile examination of the buccal tooth surfaces recorded carious lesions in 7 cases, representing 1.3% of all examined surfaces. The ERT identified 31 carious lesions, representing 22.6%. QLF diagnosed 173 carious lesions, or 13.2%. The three diagnostic methods showed highly significant pairwise differences: p1–2 = 0.004; p1–3 < 0.001; p2–3 < 0.001; p1–3 < 0.001.

In the group of 13-year-old children, visual-tactile examination of the buccal tooth surfaces recorded carious lesions in 4 cases, representing 0.9% of all examined surfaces. The ERT identified 29 carious lesions, representing 21.7%. QLF diagnosed 185 carious lesions, or 15.8%. The three diagnostic methods showed highly significant pairwise differences: p1–2 = 0.001; p1–3 < 0.001; p2–3 < 0.001; p1–3 < 0.001.

In the group of 14-year-old children, visual-tactile examination of the buccal tooth surfaces recorded carious lesions in 2 cases, representing 0.5% of all examined surfaces. The ERT identified 36 carious lesions, representing 25.2%. QLF diagnosed 177 carious lesions, or 14.4%. The three diagnostic methods showed highly significant pairwise differences: p1–2 = 0.003; p1–3 < 0.001; p2–3 < 0.001; p1–3 < 0.001.

In the group of 15-year-old children, visual-tactile examination of the buccal tooth surfaces recorded carious lesions in 4 cases, representing 0.7% of all examined surfaces. The ERT identified 38 carious lesions, representing 26.3%. QLF diagnosed 180 carious lesions, or 15.2%. The three diagnostic methods showed highly significant pairwise differences: p1–2 = 0.001; p1–3 < 0.001; p2–3 < 0.001; p1–3 < 0.001.

During WHO-based clinical examination of 7-year-old children, carious lesions were recorded on the occlusal surface in 9 cases, representing 5.1% of all examined surfaces. The ERT identified 81 carious lesions (45.8%). Quantitative light-induced fluorescence diagnosed 165 carious lesions (87.6%). The three diagnostic methods showed highly significant pairwise differences: p1–2 < 0.001; p2–3 < 0.001; p1–3 < 0.001.

In the group of 15-year-old children, visual-tactile examination of occlusal tooth surfaces detected 40 carious lesions (5.6%). The ERT identified 196 carious lesions (28.4%). QLF diagnosed 455 carious lesions (63.4%). The three diagnostic methods showed highly significant pairwise differences: p1–2 = 0.001; p1–3 < 0.001; p2–3 < 0.001; p1–3 < 0.001.

The following signs of low molar mineralization were identified in 69.9% of the examined participants:

– rough, porous, softened enamel in fissures and blind pits, and a rough, porous, softened enamel surface in the cervical, lingual, and approximal regions;

– defects, cracks, spots, and pigmentation on the surfaces of permanent teeth;

– cone-shaped, flask-shaped, and closed-type fissures;

– a low initial mineralization level;

– delayed and asymmetric eruption;

– delayed and asymmetric eruption;

The following signs of a high level of mineralization of the hard tissues of permanent molars were identified in 31.1% of the examined participants:

– dense, smooth enamel surfaces in fissures and blind pits;

– no enamel defects in the form of spots or pigmentation;

– open groove-shaped fissures;

– timely and symmetric eruption;

– a dense, smooth enamel surface in the cervical, lingual, and approximal regions.

The study showed that, in all patients who underwent the enamel resistance test, the result corresponded to the mineralization level identified using the proposed criteria.

In teeth with a high level of hard-tissue mineralization, the ERT index ranges from 10% to 30%. An ERT value greater than 30% indicates a low mineralization level. In children with a high mineralization level of the hard tissues of permanent teeth, the mean ERT value was 23.31 ± 4.35%, with a minimum of 10% and a maximum of 29.9%. In children with a low mineralization level, the mean ERT value was 56.35 ± 5.34%, with a maximum of 100% and a minimum of 30%.

Thus, higher ERT values were found in patients with a low level of mineralization of the hard tissues of permanent teeth, whereas patients with a high mineralization level had lower ERT values.

The study found no apparent loss of enamel fluorescence and no “red glow” in pits and fissures in patients with a high level of mineralization of the hard tissues of permanent teeth. Mean fluorescence loss (ΔF) ranged from 0 to −15% on tooth surfaces with a high mineralization level. In patients with a low mineralization level, the following QLF parameter values were found in 100% of cases. In children with a high mineralization level of the hard tissues of permanent teeth, mean fluorescence loss was −8.11 ± 0.67%, with a minimum of −15% and a maximum of 0%. In children with a low mineralization level, mean fluorescence loss was −22.34 ± 0.84%, with a maximum of −16% and a minimum of −29%. Thus, children with a low mineralization level of the hard tissues of permanent teeth had substantially greater mean fluorescence loss (ΔF) than children with a high mineralization level, indicating more pronounced changes in the mineral composition of the hard tissues.

Assessment of mineral loss from the hard tissues of permanent teeth with occlusal caries yielded the mean QLF parameters shown in Table 2.

Table 2. QLF parameters recorded on occlusal tooth surfaces in the different age groups.

Number of examined teeth		7–8	9–10	11–12	13–14	14–15
QLF method (Q-ray Pen)	ΔF max, mean	-42.5 ±26.1	-27.0 (-37.9; -15)	-26.2 (-40; -14.4)	-28.0 (-37.9; -15)	-27.5 (-40; -14.4)
	ΔF average	-12.9 (-16.6; -9.5)	-12.6 (-15.5; -8.8)	-11.9 (-17.0; -8.3)	-13.6 (-15.5; -8.8)	-12.2 (-17.0; -8.3)
	ΔQ [% px], mean	-86687 (-224398. -34063)	-4052 (-9998; -956)	-4673 (-19011; -1103)	-4055 (-9998; -956)	-4675 (-19011; -1103)
	White Spot Area, mean	5969 (3198; 14035)	328 (108; 637)	306 (121; 1550)	345 (108; 637)	313 (121; 1550)
	White Spot ΔR, mean	31 (25;38)	26 (21.3; 30)	26 (22.8; 32)	28 (21.3; 32)	25 (22.8; 32)
	White Spot ΔR max, mean	66 (36; 114)	36 (0; 54)	38 (0; 60.8)	34 (0; 54)	40 (0; 60.8)
	White Spot ΔR area, mean	3309 (1299; 7128)	102 (14; 331)	117 (23; 349)	108 (14; 331)	122 (23; 349)
	ΔF max, mean	-42.5 ±26.1	-27.0 (-37.9; -15)	-26.2 (-40; -14.4)	-28.3 (-37.9; -15)	-27.7 (-40; -14.4)
	ΔF average	-12.9 (-16.6; -9.5)	-12.6 (-15.5; -8.8)	-11.9 (-17.0; -8.3)	-13.4 (-15.5; -8.8)	-12.2 (-17.0; -8.3)
	ΔQ [% px], mean	-86687 (-224398. -34063)	-4052 (-9998; -956)	-4673 (-19011; -1103)	-4437 (-9998; -956)	-4741(-19011; -1103)
	White Spot Area, mean	5969 (3198; 14035)	328 (108; 637)	306 (121; 1550)	334 (108; 637)	313 (121; 1550)
	White Spot ΔR, mean	31 (25;38)	26 (21.3; 30)	26 (22.8; 32)	28 (21.3; 32)	29 (22.8; 34)
	White Spot ΔR max, mean	66 (36; 114)	36 (0; 54)	38 (0; 60.8)	50 (0; 74)	47 (0; 70.8)

White Spot ΔR area, mean	3309 (1299; 7128)	102 (14; 331)	117 (23; 349)	114(14; 331)	125 (23; 349)

Based on ΔF max values obtained during diagnosis of occlusal tooth surfaces in children, four levels of mineral loss from dental hard tissues were defined: low, ΔF max 0–20%; moderate, ΔF max 21–40%; high, ΔF max 41–60%; and very high, ΔF max ≥61%. Comparison of the maximum level of mineral loss, ΔF max [%], with the white-spot area showing bacterial activity, White Spot ΔR [%], across the age groups revealed statistically significant differences ($p < 0.05$) (Table 3).

Table 3. Comparative characteristics of ΔF max and White Spot ΔR across the defined levels in children aged 7–15 years.

Statistical parameters	ΔF max [%]	White Spot ΔR [%]
Low ΔF max level		
n	32	32
Mean	-14.0	19.4
±SD	4.7	9.8
Moderate ΔF max level		
n	50	50
Mean	-31.6	29.7
±SD	6.2	12.3
High ΔF max level		
n	33	33
Mean	-50.7	34.0
±SD	6.5	6.6
Very high ΔF max level		
n	35	35
Mean	-79.7	73.6
±SD	12.3	110.0
One-way analysis of variance (ANOVA)		
Fisher’s F-statistic	442.1	96.6
Statistical significance of differences, p	<0.001	<0.001

Comparative analysis of the defined levels in children aged 7–15 years yielded the following mean ΔF max values: low level, −14.0%; moderate level, −31.6%; high level, −50.7%; and very high level, −79.7%.

To evaluate and confirm the outcomes of remineralizing therapy with a calcium-, fluoride-, and arginine-containing gel, treatment was performed using Colgate Maximum Cavity Protection. At different stages of carious lesion development, quantitative light-induced fluorescence and the ERT were applied in all age groups at baseline and after the course of remineralizing therapy.

In the group of children aged 7–8 years, the following baseline mean values were obtained:

ΔF max, −44.4 ± 20; ΔF average, −14.9 ± 5.3; ΔQ [% px], −131,220 (−327,450; −39,559); White Spot Area, 8,481 (2,764; 18,359); White Spot ΔR [%], 32 (30; 39); White Spot ΔR max [%], 86 (61; 114); White Spot ΔR area, 3,880 (2,071; 9,574); ERT, 48.83 ± 5.02, corresponding to a low mineralization level.

After remineralizing therapy with a calcium-, fluoride-, and arginine-containing gel and Colgate Maximum Cavity Protection toothpaste, the following mean values were obtained in children aged 7–8 years: ΔF max, −29.4 ± 16.3; ΔF average, −10.4 ± 4.9; ΔQ [% px], −52,036 (−175,053; −17,740); White Spot Area, 3,405 (951; 7,654); White Spot ΔR [%], 23 (19.5; 30.5); White Spot ΔR max [%], 45 (25.5; 72.5); White Spot ΔR area, 2,259 (814; 8,099); ERT, 37.74 ± 4.59.

In the group of children aged 9–10 years, the following baseline mean values were obtained:

ΔF max, −25.8 (−34.1; −15.0); ΔF average, −12.3 (−14.6; −8.6); ΔQ [% px], −3,163 (−8,314; −849); White Spot Area, 278 (94; 853); White Spot ΔR [%], 26.5 (21; 31); White Spot ΔR max [%], 36 (0; 56); White Spot ΔR area, 134 (17; 406); ERT, 56.35 ± 5.34, corresponding to a low mineralization level.

After remineralizing therapy, the following mean values were obtained in children aged 9–10 years: ΔF max, −15.1 (−21.4; −5.9); ΔF average, −8.0 ± 5.8; ΔQ [% px], −547 (−3,085; −41); White Spot Area, 79 (6; 372); White Spot ΔR [%], 11.5 (0; 26.3); White Spot ΔR max [%], 0 (0; 47); White Spot ΔR area, 5 (0; 104); ERT, 46.84 ± 4.91.

In the group of children aged 11–12 years, the following baseline mean values were obtained:

ΔF max [%], −33.9 ± 22.1; ΔF average [%], −12.5 (−16.2; −8.8); ΔQ [% px], −6,460 (−58,353; −2,005); White Spot Area [px], 380 (181; 5,037); White Spot ΔR [%], 30 ± 14.8; White Spot ΔR max [%], 39 (0; 69); White Spot ΔR area [px], 216 (46; 1,883); ERT, 50.08 ± 5.31, corresponding to a low mineralization level.

After remineralizing therapy, the following mean values were obtained in children aged 11–12 years: ΔF max, −22.6 ± 18.9; ΔF average, −7.4 (−10.4; −5.2); ΔQ [% px], −2,534 (−33,643; −262); White Spot Area, 233 (102; 3,312); White Spot ΔR [%], 16.7 ± 14.2; White Spot ΔR max [%], 16 (0; 35.8); White Spot ΔR area, 103 (0; 811); ERT, 41.35 ± 4.64.

In the group of children aged 13–14 years, the following baseline mean values were obtained:

ΔF max [%], −33.9 ± 22.1; ΔF average [%], −12.5 (−16.2; −8.8); ΔQ [% px], −6,460 (−58,353; −2,005); White Spot Area [px], 380 (181; 5,037); White Spot ΔR [%], 30 ± 14.8; White Spot ΔR max [%], 39 (0; 69); White Spot ΔR area [px], 216 (46; 1,883); ERT, 50.08 ± 5.31, corresponding to a low mineralization level.

After remineralizing therapy, the following mean values were obtained in children aged 13–14 years: ΔF max, −22.6 ± 18.9; ΔF average, −7.4 (−10.4; −5.2); ΔQ [% px], −2,534 (−33,643; −262); White Spot Area, 233 (102; 3,312); White Spot ΔR [%], 16.7 ± 14.2; White Spot ΔR max [%], 16 (0; 35.8); White Spot ΔR area, 103 (0; 811); ERT, 41.35 ± 4.64.

In the group of children aged 14–15 years, the following baseline mean values were obtained:

ΔF max, −25.8 (−34.1; −15.0); ΔF average, −12.3 (−14.6; −8.6); ΔQ [% px], −3,163 (−8,314; −849); White Spot Area, 278 (94; 853); White Spot ΔR [%], 26.5 (21; 31); White Spot ΔR max [%], 36 (0; 56); White Spot ΔR area, 134 (17; 406); ERT, 56.35 ± 5.34, corresponding to a low mineralization level.

After remineralizing therapy, the following mean values were obtained in children aged 14–15 years: ΔF max, −15.1 (−21.4; −5.9); ΔF average, −8.0 ± 5.8; ΔQ [% px], −547 (−3,085; −41); White Spot Area, 79 (6; 372); White Spot ΔR [%], 11.5 (0; 26.3); White Spot ΔR max [%], 0 (0; 47); White Spot ΔR area, 5 (0; 104); ERT, 46.84 ± 4.91.

Comparative analysis showed that, both before and after remineralizing therapy, statistically significant differences between the 7–8-year and 9–10-year groups were observed for all parameters ($p < 0.05$) except ΔF average [%].

Similarly, before and after treatment, statistically significant differences between the 7–8-year and 12–13-year groups were observed for all parameters ($p < 0.05$), except baseline ΔF average [%].

In all three age groups, remineralization produced a similar statistically significant decrease in QLF parameters (negative percentage changes, d%) and a decrease in ERT values ($p < 0.05$).

When assessing differences in the principal parameters after remineralizing therapy—the maximum mineral loss, ΔF max [%], and the white-spot area with bacterial activity, White Spot ΔR [%]—relative to corresponding values within the same age group across different levels, between identical levels in different age groups, and within age groups and their comparison groups, the values shown in the jitter plots were obtained (Fig. 1).

Fig. 1. Jitter plot for the enamel resistance test

The study found no apparent loss of enamel fluorescence and no “red glow” in pits and fissures in patients with a high level of mineralization of the hard tissues of permanent teeth. Mean fluorescence loss (ΔF) ranged from 0 to −15% on tooth surfaces with a high mineralization level. In patients with a low mineralization level, QLF showed characteristic parameter values in 100% of cases. Mean fluorescence loss (ΔF) in patients with low enamel mineralization ranged from −16% to −29%.

In children with a high level of mineralization of the hard tissues of permanent teeth, mean fluorescence loss was −8.11 ± 0.67%, with a minimum of −15% and a maximum of 0%. In children with a low mineralization level, mean fluorescence loss was −22.34 ± 0.84%, with a maximum of −16% and a minimum of −29%. Thus, children with a low mineralization level of the hard tissues of permanent teeth showed substantially greater mean fluorescence loss (ΔF) than children with a high mineralization level, indicating more pronounced changes in hard-tissue mineral composition (Fig. 2).

Fig. 2. Comparison of mean fluorescence loss (ΔF average) in children with different levels of mineralization of the hard tissues of permanent teeth. The diagram presents individual mean fluorescence-loss values as a jitter plot overlaid on a boxplot, allowing simultaneous assessment of the data distribution, median, interquartile range, and variability in each group. Blue indicates children with a high mineralization level, and orange indicates children with a low mineralization level. Diamonds represent the means, and vertical bars show the 95% confidence intervals. Each group included 329 children.

Statistical analysis revealed highly significant differences between children with high and low mineralization levels of the hard tissues of permanent teeth ($p < 0.0001$), demonstrating a close association between enamel mineralization and mean fluorescence loss. More negative ΔF average values in children with low mineralization reflect more pronounced enamel demineralization and reduced structural resistance.

These findings demonstrate that mean fluorescence loss is a sensitive quantitative marker of the mineralization status of the hard tissues of permanent teeth. The substantial decrease in ΔF average in children with a low mineralization level confirms the diagnostic value of this parameter for early detection of enamel demineralization and assessment of caries risk.

Conclusion and Discussion

The findings confirm the high diagnostic value of quantitative light-induced fluorescence (QLF) and the enamel resistance test (ERT) for detecting the initial stages of demineralization of permanent tooth enamel in school-aged children. The combined use of these methods enabled both objective assessment of the mineralization of dental hard tissues [8–13] and quantitative determination of the depth and severity of demineralization before the formation of a clinically evident carious cavity. This is consistent with contemporary concepts of minimally invasive dentistry [3, 18, 19], according to which diagnosis should focus on identifying preclinical enamel changes and initiating remineralizing therapy in a timely manner.

One of the most important findings was the close association between enamel mineralization and ERT values. In children with a high mineralization level, the mean ERT value was 23.31 ± 4.35%, whereas in children with a low mineralization level it increased to 56.35 ± 5.34%. Thus, higher ERT values reflect reduced enamel acid resistance and a lower mineral content, confirming the diagnostic value of the test as a simple and accessible method for assessing caries risk.

The quantitative light-induced fluorescence findings were equally informative. Mean fluorescence loss (ΔF average) was −8.11 ± 0.67% in children with a high mineralization level and −22.34 ± 0.84% in those with a low mineralization level; the between-group difference was highly significant ($p < 0.0001$). More negative ΔF values reflect greater loss of enamel minerals and indicate progression of demineralization. These data demonstrate that ΔF average is highly sensitive to changes in enamel structure and may serve as an objective quantitative biomarker of the early carious process.

The high diagnostic value of QLF was further supported by its substantially greater sensitivity than traditional visual-tactile examination. In all age groups, QLF identified considerably more foci of demineralization than clinical examination and the ERT, particularly during the early stages of lesion development. This is explained by the ability of quantitative light-induced fluorescence to record changes in the optical properties of enamel resulting from mineral loss long before visible clinical signs of caries appear.

The findings are also consistent with evidence supporting remineralizing therapy using products containing fluoride, calcium, and arginine [20–29, 31, 33, 34]. After treatment, all age groups showed statistically significant decreases in ΔF max, ΔF average, ΔQ, the area of demineralization (White Spot Area), bacterial activity (White Spot ΔR), and ERT values. These changes indicate restoration of enamel mineral density, reduced depth of demineralization, and increased acid resistance of the dental hard tissues.

Quantitative light-induced fluorescence has an important advantage over most traditional diagnostic methods [9–13, 17, 32, 35, 37], because it enables objective documentation of changes in enamel status over the course of treatment. The availability of quantitative measurements makes the method particularly valuable for monitoring preventive interventions and evaluating the outcomes of remineralizing therapy, as confirmed by the present findings.

A 2024 meta-analysis considered hydroxyapatite-containing products a promising adjunct for caries prevention and remineralization, while emphasizing the need for further independent randomized studies [31]. In 2025, the European Commission Scientific Committee on Consumer Safety updated its assessment of nano-hydroxyapatite in oral-care products and considered it safe at the specified concentrations when restrictions on particle morphology are observed [33]. A preliminary Bayesian meta-analysis published in 2025 also reported a pronounced preventive effect of fluoride varnish; however, the study is a preprint and should be interpreted after peer review [34]. Studies from 2025–2026 demonstrate the active introduction of artificial intelligence into caries diagnosis [35, 37] and the development of computational models for hydroxyapatite modification to improve its chemical stability [36]. Because references [34–37] are preprints, they are presented as promising research directions and were not used as the principal evidence base for the clinical conclusions.

Study limitations include recruitment of children from a single region and the absence of long-term follow-up after completion of remineralizing therapy. Future multicenter studies with longer observation

periods are warranted to assess the durability of the remineralizing effect and determine the prognostic value of QLF and ERT parameters for the development of caries in permanent teeth.

Conclusions:

1. The clinical study of 658 children aged 7–15 years showed that the mineralization level of the hard tissues of permanent teeth is a key factor determining their resistance to demineralization and initial caries development.

2. The enamel resistance test (ERT) objectively reflects the degree of enamel mineralization. The mean ERT value was 23.31 ± 4.35% in children with a high mineralization level and 56.35 ± 5.34% in those with a low mineralization level, indicating a pronounced reduction in enamel acid resistance when mineralization is inadequate.

3. Quantitative light-induced fluorescence (QLF) demonstrated high sensitivity for detecting early foci of demineralization. Mean fluorescence loss (ΔF average) was −8.11 ± 0.67% in children with a high mineralization level and −22.34 ± 0.84% in children with a low mineralization level ($p < 0.0001$), confirming a strong association between mineral loss and reduced enamel fluorescence.

4. Compared with visual-tactile examination, QLF detects substantially more initial carious lesions in all age groups, confirming its advantage for the early diagnosis of concealed enamel demineralization and assessment of caries risk.

5. Remineralizing therapy with products containing fluoride, calcium, and arginine was accompanied by statistically significant improvements in mineralization parameters: decreases in ΔF max, ΔF average, ΔQ, the area of demineralization (White Spot Area), bacterial activity (White Spot ΔR), and ERT values in all studied age groups ($p < 0.05$). These findings demonstrate the effectiveness of the proposed regimen for the prevention and treatment of initial caries.

6. The combined use of QLF and the ERT provides an objective quantitative assessment of dental hard tissues, enables timely detection of the initial stages of demineralization, allows individual caries risk to be determined, and supports monitoring of remineralizing therapy. The findings justify the implementation of this diagnostic algorithm in pediatric dental practice for personalized caries-prevention programs.

Declarations

Ethical standards

The clinical protocols were approved by the Ethics Committee of Tashkent State Medical University (Resolution No. 341-S22097511 dated 5 March 2026).

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Conflict of interest.

The authors declare that they have no conflicts of interest.

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Author Contribution

Zhabborov Azizbek Ulugbek ugli wrote the main manuscript text and Yakubova Farida Kholdarovna prepared figures 1-3. All authors reviewed the manuscript."

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Figures

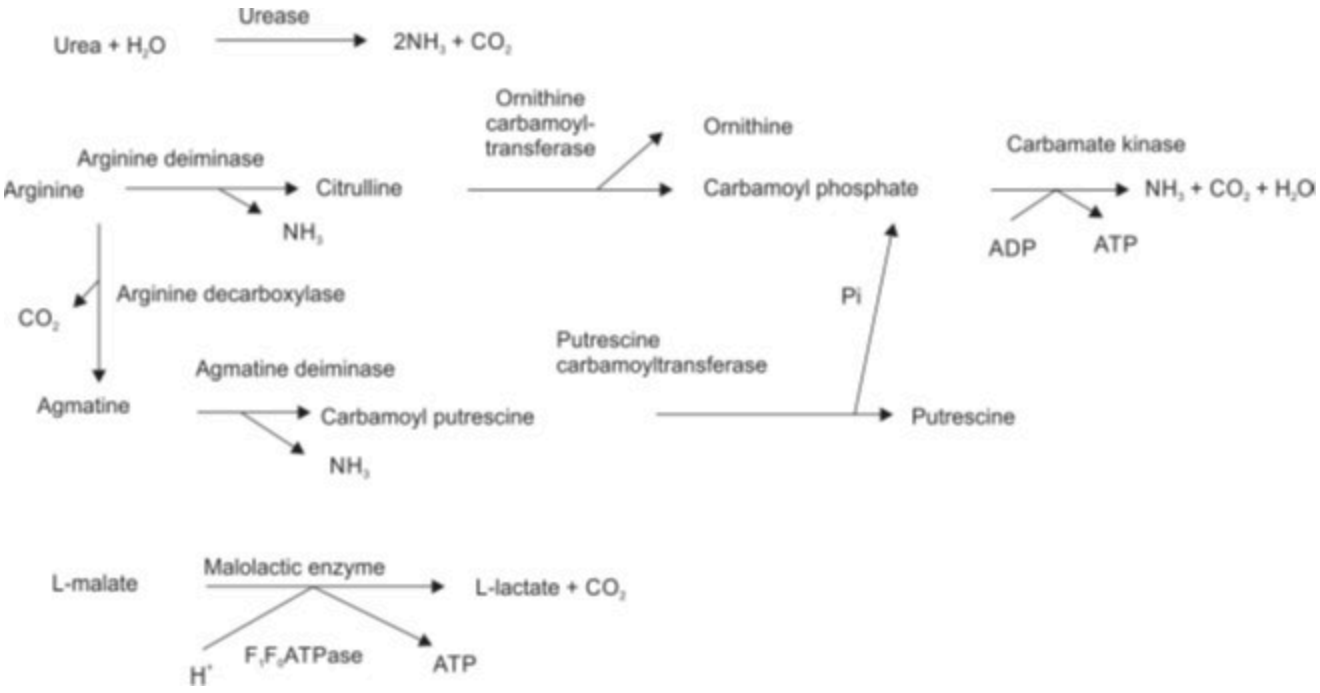


Figure 1

Fig. 1. Overview of alkali-generating pathways in the oral cavity

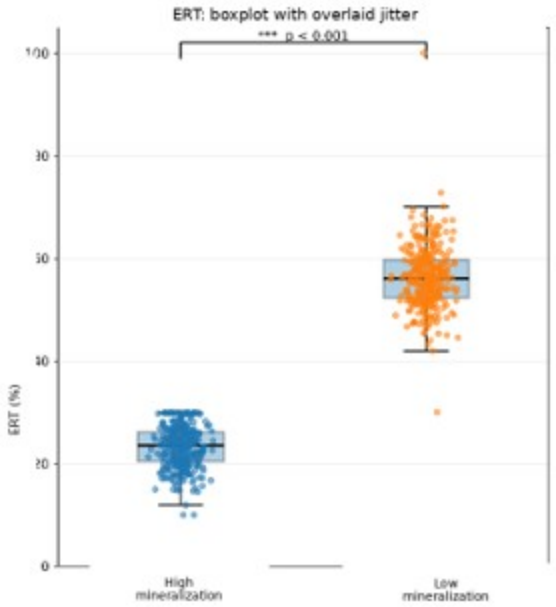


Figure 2

Fig. 1. Jitter plot for the enamel resistance test

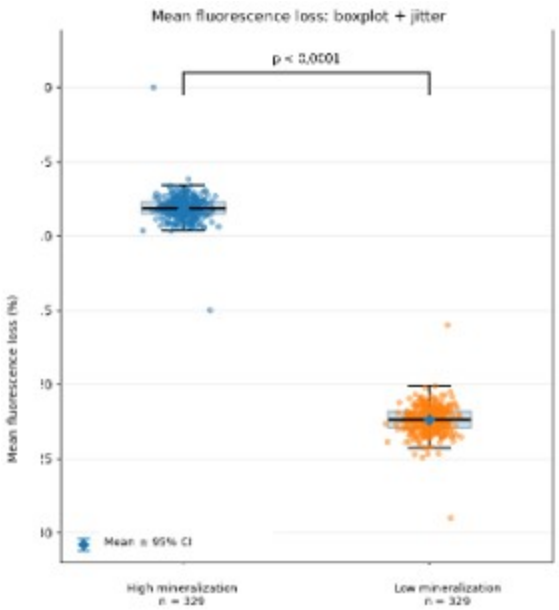


Figure 3

Fig. 2. Comparison of mean fluorescence loss (ΔF average) in children with different levels of mineralization of the hard tissues of permanent teeth. The diagram presents individual mean fluorescence-loss values as a jitter plot overlaid on a boxplot, allowing simultaneous assessment of the data distribution, median, interquartile range, and variability in each group. Blue indicates children with a high mineralization level, and orange indicates children with a low mineralization level. Diamonds represent the means, and vertical bars show the 95% confidence intervals. Each group included 329 children.