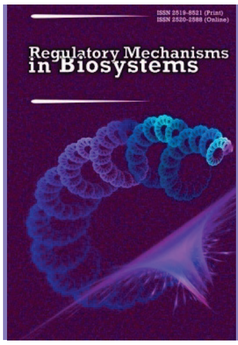

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Morphological evaluation of the effectiveness of the "Icon" resin infiltration method in acute and chronic superficial dental caries

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The article presents the results of electron microscopy of 52 teeth with acute and chronic initial caries infiltrated with "Icon" material (DMG, Germany). According to the results of the study, in acute initial dental caries (white spot stage), the infiltrate filled almost the entire volume of the pathological focus (81.8 ± 6.7% of cases). The technique of infiltration by replacing the lost mineral with a low-viscosity light-curing resin creates a barrier inside the carious lesion. Minimally invasive approaches, including the enamel infiltration technique, can be used for caries in the white spot stage for therapeutic-prophylactic purposes. However, in the case of chronic initial caries (pigmented spot stage), the infiltrate does not infiltrate the entire depth of the lesion. In 79.0 ± 9.4% of the teeth of this group, non-infiltrated areas of carious lesions were localized within the surface layers of dentin. Extrapolating the results obtained to the clinic, we can assume that the infiltration of initial caries at the stage of a pigmented spot does not ensure the stabilization of the carious process. Clinical recommendation of the low-viscosity resin infiltration technique requires evidence that requires long-term clinical observations.

Keywords: teeth; enamel; focal demineralization; caries; microinvasive treatment; infiltration with resin; electron microscopy.

Introduction

Modern paradigms of dental caries treatment are focused on biological approaches to the treatment of the disease and its main manifestation – carious lesions (Zero, 1999). Today, we can trace the evolution of carious lesions treatment from surgical and invasive approaches of the era of Greene Vardiman Black, the founder of dentistry, in which the American scientist described the principle of "preventive expansion of the carious cavity" to the modern period of minimally invasive biological approaches (Gray & Shellis, 2002; Cebula et al., 2023; Philip & Suneja, 2023). Minimally invasive dentistry can be defined as a philosophy of professional treatment that deals with early diagnosis and the earliest possible treatment of the disease at the micro level (Calache et al., 2013; Tassery et al., 2013). The dominance of micro-invasive treatment in modern thinking helps to eliminate very common patient anxieties caused by traditional surgical dental procedures, such as anesthesia and carious cavity preparation (Zhou et al., 2018; Tang & Huang, 2019; Adham et al., 2021; Pascareli-Carlos et al., 2021). Minimal interventions (MID) are especially important in the practice of pediatric therapeutic dentistry (Altarabulsi et al., 2014). Today, there is a shift away from the narrow focus of mechanical operative approaches to dental caries treatment to an approach that embraces new strategies for caries prevention and treatment, implemented in the context of partnership with children (Kagihara et al., 2009; Gussy et al., 2016; Innes & Manton, 2017). The resin infiltration (RI) technique was introduced as one of the minimally invasive strategies in dentistry for the treatment of dental caries among children (Dziaruddin & Zakaria, 2022).

The main method of treating tooth enamel caries is still remineralizing therapy, as before (Martens & Verbeeck, 1998; Lussi et al., 2012; Amaechi & van Loveren, 2013; Flemming et al., 2022; Lubojanski et al., 2023). In recent years, a new method has been proposed that occupies an intermediate place between remineralizing therapy and operative and restorative treatment of dental caries in the stain stage – the method of tooth enamel infiltration (Perdigão, 2020; Allen et al., 2021; Xie et al., 2023). In 2009, an alternative approach to microinvasive treatment of noncavitated dental caries was proposed (Kugel et al., 2009; Phark et al., 2009). The method of microinvasive treatment was developed by Meyer-Lueckel (Meyer-Lueckel et al., 2012) and implemented in practice by DMG (Germany) in a product called "Icon". According to the manufacturer's annotation, the Icon material can be used to treat caries from E1 (surface layers of enamel) to D1 (surface layers of dentin) according to the radiological classification of the depth of carious lesions (Wenzel, 2021). The method is based on the removal of a dense, poorly permeable pseudo-intact enamel layer with hydrochloric acid and subsequent filling of the lesion with a mixture of high-flow synthetic resins with certain rheological characteristics (Alsafi & Taher, 2023). This technique uses a low-viscosity resin monomer to infiltrate non-cavitated carious lesions, which allows the tooth structure to be preserved (Dziaruddin & Zakaria, 2022). Only one "Icon" penetration material, (DMG), is available on the market and new chemical formulations are currently being investigated to further exploit the advantages of the resin infiltration technique (Mazzitelli et al., 2022). The method of enamel infiltration with resin opens up a new range of minimally invasive treatment of dental caries in the stain stage, helps to improve aesthetics in one visit (Ibrahim et al., 2023).

The purpose of the study is – to evaluate the effectiveness of the method of enamel infiltration in the stage of white and pigmented spots with the material "Icon" (DMG, Germany) using scanning electron microscopy (SEM).

Materials and methods

The research was conducted in accordance with the guidelines "Compliance with ethical and legal norms and requirements in the performance of scientific morphological research" and in compliance with the main provisions of the Helsinki Declaration of the World Medical Association about ethical principles for medical research involving humans (1964–2000), the main bioethical provisions of the Council of Europe Convention on Human Rights and Biomedicine (dated 04.04.1997) and Order of the Ministry of Health of Ukraine No. 690 dated September 23, 2009, in compliance with all necessary legal and administrative requirements. Bioethical expertise of scientific research on research methods was carried out and compliance with international and Ukrainian legal standards was confirmed at a meeting of the Bioethics Commission of I. Horbachevsky Ternopil National Medical University (protocol No. 21 dated January 8, 2020). Written informed consent for participation in the study was obtained from the patients. Violations of moral and ethical norms during the conduct of research work were not detected.

The laboratory model was 52 primary teeth with enamel caries, which had been extracted for medical reasons. The teeth were divided into two groups according to the clinical form of caries. The first group consisted of 33 (63.5%) teeth with enamel caries in the form of a white spot (acute superficial caries). Second – 19 (36.5%) teeth with pigmented (yellow and brown) spots (chronic superficial caries). Since the vital teeth in the oral cavity contain more fluid, which can prevent the penetration of hydrophobic material, the teeth were infiltrated with "Icon" material before their extraction. This made it possible to bring the results of the laboratory test as close as possible to the in vivo condition. The study was carried out using a scanning electron microscope with a "JEOL-25M-T220A" auto-emission cathode (Tokyo Boeki, Japan) with an accelerating voltage of 1 to 10 kV on the basis of the Center for Nanotechnology of Vasyl Stefanyk Precarpathian National University. To assess the quality of infiltration, the depth of penetration of the infiltrate into the enamel thickness, its uniformity and the presence of uninfiltrated areas of carious lesions (filling defects) were studied. The quality of infiltration with the "Icon" material was determined as follows. In the central part of the infiltrated area of enamel caries along the "Icon"/enamel interface, 3 scans were taken sequentially with a magnification of 500–600 times. The maximum and minimum values of the infiltration depth, as well as the presence or absence of a filling defect, were determined at each of them. The unevenness of the infiltration depth was determined as the average value of the difference between the maximum and minimum depth of infiltration. Clarification of theoretical and practical conclusions, generalization and systematization of results was carried out using methods of mathematical statistics. Information displayed in the table is expressed as x ± SD (mean ± standard deviation). Tukey's test was used to compare mean values between two experimental groups. Notably, statistical significance was recognized at $P < 0.05$ for all data presented.

Results

During microscopic examination (magnification $^{\times}250$) of the samples of both groups, the structure of the infiltrated enamel area was determined as a homogeneous conglomerate devoid of noticeable structural elements of enamel. The polymerized material was visually identified as shiny areas in contrast to the more matte healthy enamel. At a magnification of 500–600 times in all samples, a relative unevenness (scalloping) of the infiltrate penetration into the enamel thickness was noted, as a result of which the "Icon"/enamel interface had a wavy contour (Fig. 1a). Microphotographs with a magnification of 2000–2500 times show a uniformly increasing penetration of the polymerized resin into the inter-prism space. At the same time, unlike healthy enamel, structural elements (enamel prisms) after treatment of initial caries by infiltration are visualized much worse due to the homogeneity of the infiltrated area (Fig. 1b).

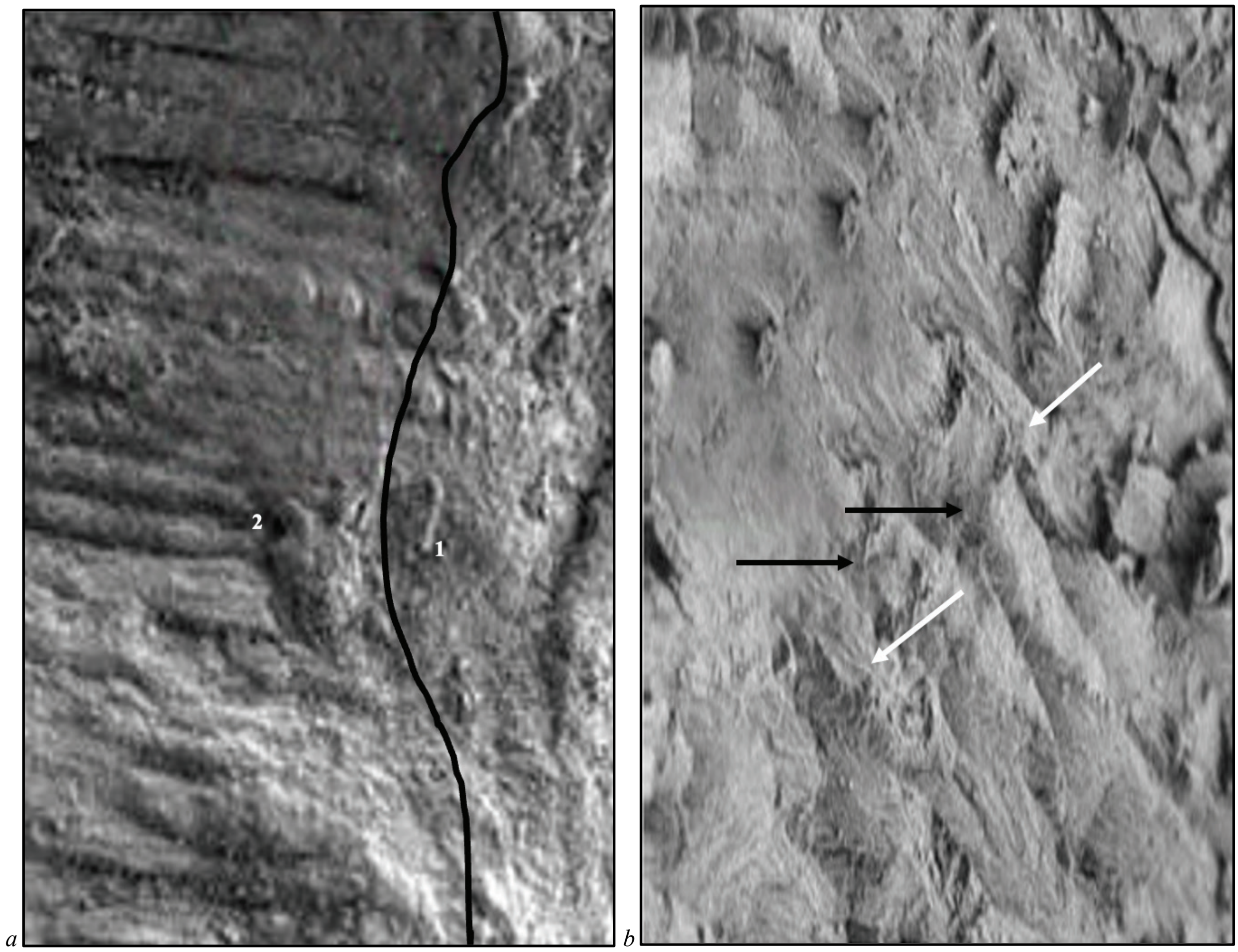

Fig. 1. The area of infiltrated enamel of a white carious spot: *a* – uneven penetration of the infiltrate into the enamel thickness (the border between infiltrated (*1*) and non-infiltrated enamel (*2*) is marked with a black line) ($^{\times}600$); *b* – penetration of the infiltrate (indicated with white arrows) into the inter-prism space (enamel prisms are shown by black arrows) ($^{\times}2500$)

Non-infiltrated areas of carious lesions (filling defects) were defined as areas of enamel with clearly visible structural elements, but with signs of demineralization. In the zone of carious lesion infiltration, bubble-like filling defects are clearly visible (Fig. 2).

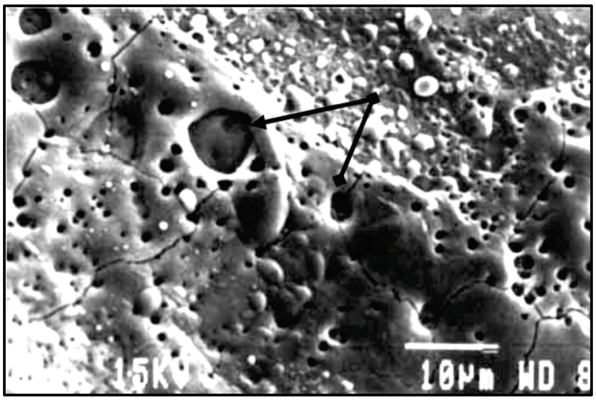

Fig. 2. Enamel structure in the zone of carious lesion infiltration with clear bubble-like filling defects (indicated with black arrows): scanning electron microscopy; accelerating voltage 15 kV, scale bar = 10 µm

In demineralized enamel, the inter-prism spaces contain a much smaller amount of hydroxyapatite crystals compared to healthy enamel, as a result of which the enamel prisms are more clearly defined. Thus, due to the visually distinctive surfaces of different areas of the grindings (infiltrated area, demineralized non-infiltrated area, and healthy enamel area), quite clear boundaries can be traced between them (Fig. 3).

During the examination of the depth of the enamel caries focus (50- and 70-times magnification), it turned out that in the group of teeth with white carious spots, in 33 (100%) cases the carious process was localized in the superficial layers of the enamel. The average depth of infiltration in the group of white carious spots was 119.4 ± 3.5 µm. In 27 (81.8%) cases, this depth corresponded to the depth of the caries process, as a result of which no filling defects were detected (Fig. 4a). In addition, in the vast majority of cases (more than 80%), at a magnification of 1000 times, infiltration into the inter-prismal spaces of healthy enamel to a depth of 30 µm was noted (Fig. 4b).

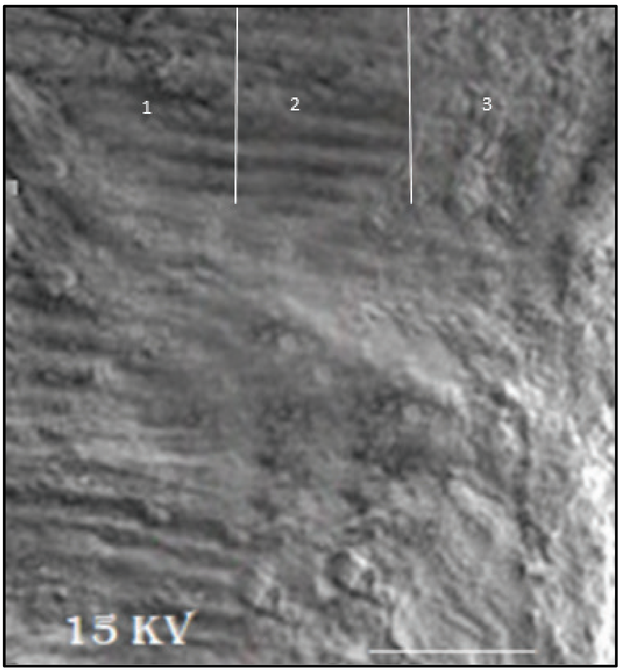

Fig. 3. Micrograph of the enamel area infiltrated with "Icon" material (*1*), enamel filling defect (*3*) and the boundary between them (*2*) (×1000)

During the preparation of the teeth for microscopy, dentin lesions were visible in teeth with caries at the stage of a pigmented spot (Fig. 5a). SEM showed that in the group of teeth with pigmented spots in 15 (79.0%) cases, the presence of a carious process within the dentin was detected (Fig. 5b).

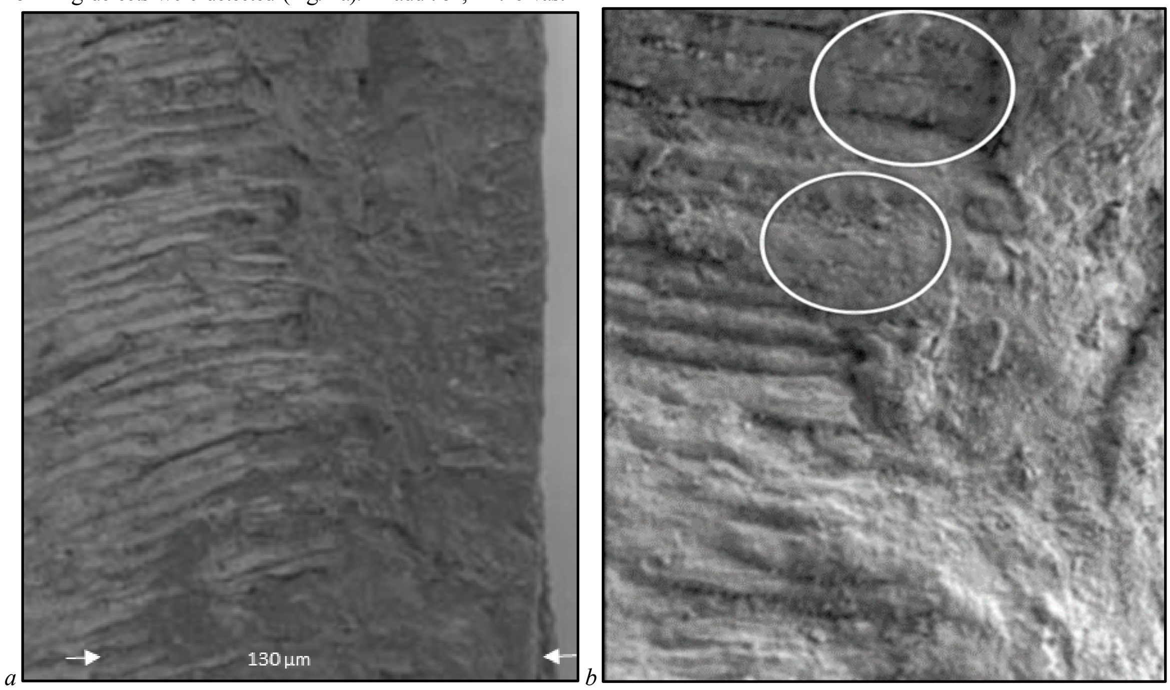

Fig. 4. Infiltrated area of white spot (group 1): *a* – the area of initial caries is filled with polymer resin along its entire length up to the healthy enamel; there are no filling defects; the maximum depth of infiltration in this case was 130 µm (the boundaries of the infiltrated enamel are indicated with white arrows) (×500); *b* – infiltration of the infiltrate into the inter-prismal spaces of healthy enamel (highlighted in white) (×1000)

The average depth of infiltration of the infiltrate in the group of pigmented carious spots was 91.2 ± 3.4 µm ($P < 0.001$). This depth was less than the depth of the carious process, as a result of which filling defects were found both within the enamel and dentin (Fig. 5b). Infiltration of the material into the dentin was not observed in any of the samples of group 2. The values of the maximum and minimum depths of infiltration, as well as the values of the unevenness of filling the hard tissues of the teeth with infiltrate in groups 1 and 2 are presented in Table 1. The depth of infiltration in the group with white carious spots was 25% greater ($P < 0.005$) than in the group with pigmented spots. The unevenness of the infiltration obviously indirectly indicates the unevenness of the carious process in the enamel thickness. In this case, it was approximately equal in the two groups and amounted to about 75% of the maximum depth of infiltration in each of them. Thus, in the case of white carious spots, the infiltration technique proved to be quite effective. In this group, homogeneous infiltration of the area of initial caries was noted throughout its entire length in 81.8 ± 6.7% of cases. At the same time, the volume of filling defects is minimized. This is likely to increase the resistance of hard tooth tissues to pathogenic factors and stop further progression of caries in the white spot stage *in vivo*. In addition, the polymerized resin allows for mechanical stabilization of fragile demineralized tooth enamel. Resin infiltration can be considered a safe and effective treatment method to reduce the progression of acute initial caries. Complete isolation of the infiltrated focus of initial caries from healthy enamel allows us to talk about the preventive component of the infiltration method. However, in the case of pigmented spots, there is no infiltration of the lesion to its full depth. In all samples, non-infiltrated areas of the carious lesion were found. Thus, in 78.9 ± 9.4% of cases, they were localized only within the surface layers of dentin. This is in line with the opinion of Featherstone (2004) and Pugach et al. (2009), who consider pigmented spots to be dentin caries in nature. Extrapolating the results obtained to the clinic, we can assume that the infiltration of initial caries at the stage of pigmented spots does not ensure the stabilization of the carious process.

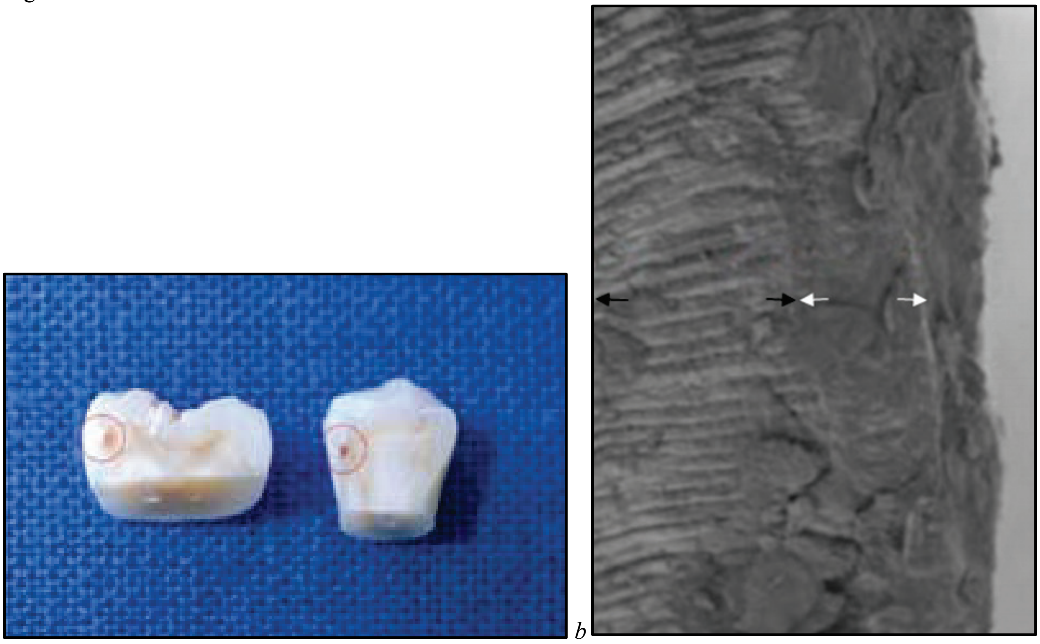

Fig. 5. Samples of teeth with enamel caries in the form of a pigmented spot (group 2): *a* – visible dentin lesion in teeth with enamel caries in the form of a pigmented spot, detected during preparation of teeth for microscopy; *b* – infiltrated area (highlighted by white arrows) of enamel caries in the form of a pigmented spot with a magnification of 500 times; there is a significant amount of demineralized enamel not filled with infiltrate (filling defect is highlighted by black arrows) ($^{\times}500$)

Table 1
Comparative depth of penetration of the "Icon" material and the value of unevenness (μm) in the infiltration of white and pigmented carious spots according to the results of electron microscopy

Groups of teeth samples	Maximum penetration depth of the infiltrate, μm	Minimum penetration depth of the infiltrate, μm	The value of infiltration irregularity, μm
Group 1 (white spots), n = 33	119.42 ± 3.48^a	30.31 ± 2.26^b	89.14 ± 4.11^c
Group 2 (pigmented spots), n = 19	91.23 ± 3.37^a	20.61 ± 2.02^b	70.63 ± 3.12^d

Note: different letters in a row indicate that data samplings are significantly ($P < 0.05$) different one from another according to the Tukey test with the Bonferroni correction.

Discussion

Despite the introduction of the latest technologies for preventing dental caries, there has been an increase in the incidence in recent years, which has no tendency to stabilize. Unfortunately, the implemented comprehensive caries prevention measures do not always demonstrate high efficiency (Kudiyirickal & Ivancaková, 2008). The demand for aesthetic dentistry has led to the development of new methods of treating dental caries at the stage of white spots. The pathophysiology of caries is a dynamic process characterized by alternating periods of de- and remineralization. According to modern views, enamel demineralization is the main mechanism involved in the etiopathogenesis of dental caries. In case of dental caries, this process is mediated by a biofilm. During the formation of focal demineralization, decalcification occurs under the influence of organic acids, in which hydrogen protons (H^+) displace calcium ions (Ca^{2+}) and bind to hydroxyapatite. The concentration of hydrogen protons increases as the environment becomes acidic. The released Ca^{2+} is used to neutralize acidic products of the oral fluid (Zero, 1999). When calcium ions leave the crystal lattice, the Ca/P ratio in the enamel decreases, resulting in a decrease in the ability of crystals to resist acid, and demineralization processes prevail over remineralization processes. Due to the dynamics of caries development, it is possible to stop and even restore it in the early stages without operative intervention by increasing the net mineral gain during the cycles of demineralization and remineralization (González-Cabezas, 2010). The loss of mineral, which leads to the dissolution of the hard tissues of the tooth, causes tooth decay, which can be seen clinically. Significant pH fluctuations in the biofilm on the tooth surface are a natural phenomenon, the result of which can be recorded in the tooth tissues only at the chemical or ultrastructural level (subclinical level) (Kidd & Fejerskov, 2004; Ivancaková, 2008; Kudiyirickal & Ivancaková, 2008; Bin-Jardan et al., 2023).

To date, there is no clear understanding of the ultramorphology of the carious process at the stage of white spot (WSL) on the enamel and the morphological characteristics of resin infiltration of WSL enamel. Welch et al. (2023) used three-dimensional photothermal imaging methods to monitor caries progression: truncated correlation photothermal coherence tomography (TC-PCT) and its improved modification eTC-PCT, as well as microcomputed tomography (μ-CT). The results of the authors' observations demonstrated high sensitivity and the possibility of depth profiling with thermophotonic modalities for the early detection of dental caries. Lo et al. (2010), comparing the detected changes before and after remineralization of artificial enamel and dentin caries using micro-CT, polarized light microscopy (PLM) and transverse micro-radiography (TMR), found a decrease in the average depth of hard tissue lesions. The treatment of demineralized enamel using microinvasive treatments such as resin infiltration, specifically using the active ingredient triethylene glycol dimethacrylate (TEGDMA), has been reported. Studies by Allen et al. (2021) show that resin infiltration with TEGDMA removes a minimal amount of enamel and preserves the hard tissue surrounding the WSL. In addition, TEGDMA restores the natural fluorescence, hardness and texture of intact enamel and is an effective alternative treatment option for WSLs.

Some studies show that the results of microinvasive procedures using resin infiltration may differ depending on the depth of the lesion. Saghiri et al. (2023) examined changes in surface microhardness, compressive strength, and diameter tensile strength (DTS) under the influence of L-ascorbic acid 2-phosphate (AA2P) salts of Mg, Zn, Mn, Sr, and Ba. Using scanning electron microscopy, the authors found that all hardening solutions provided some protection against artificial caries. The microhardness and compressive strength were significantly higher at a depth of 500 µm than at a depth of 100 µm. Consequently, these elements could penetrate the demineralized dentin and strengthen it against acid dissolution. Using electron microscopy, Perdigão (2020) examined enamel sections with healthy enamel and sections of carious lesions infiltrated with Icon-Etch, Icon-Dry, and Icon-Infiltrant resins. The author found that the WSL replicas showed hairy polymeric marks 0.5–6.0 µm thick to a depth of 465 µm; enamel crystallites were enveloped by resin at the bottom of the WSL, forming a hybrid layer that makes the resin-enameled enamel more resistant to acid.

Conclusions

The "Icon" material tested by us showed significant differences in the adhesive infiltration of polymer resin into demineralized tooth enamel, namely the depth of remineralization in white and pigmented caries spots. The SEM study conducted by us demonstrated the penetration of the infiltrate of Icon resin in acute initial dental caries to a depth of 30.3 to 119.4 µm, which in 81.8% of cases filled almost the entire volume of the pathological focus. In this way, the infiltration technique creates a barrier inside the carious lesion by replacing the lost mineral with a low-viscosity light-curing resin. At the same time, in chronic initial caries, the resin does not infiltrate the entire depth of the lesion: in 78.9% of samples, uninfiltrated areas of the carious lesion were localized within the surface layers of dentin. Thus, modern ion-releasing dental materials can induce remineralization of the carious lesion, prevent further loss of tooth tissue, and demonstrate chromatic stability of infiltrated lesions. White spots on tooth enamel in aesthetically compromised areas are clinically undesirable. Minimally invasive approaches, including low-viscosity resin infiltration techniques, can be used for therapeutic and prophylactic purposes, but long-term clinical observations are required to make a clinical recommendation.

The authors declare no conflict of interest.

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