

MICRO-CT EVALUATION OF RESIN INFILTRATION IN ARTIFICIAL WHITE SPOT LESIONS: COMPARISON OF STANDARD AND MODIFIED ICON PROTOCOLS

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Abstract

Our study evaluated the effect of ICON resin infiltration on artificially induced white spot lesions using micro-computed tomography (micro-CT). Sixty extracted human teeth were randomly allocated into three groups: control, ICON standard protocol, and ICON modified protocol, with 20 specimens in each group. After artificial lesion formation, baseline micro-CT confirmed comparable lesion depth, lesion volume, mineral density reduction, and initial porosity among groups. Following treatment, micro-CT was used to assess penetration depth, percentage of infiltrated lesion volume, residual porosity, lesion volume reduction, and regional three-dimensional infiltrant distribution. Substantial resin penetration was observed in both ICON-treated groups, while no resin-dependent infiltration variables were applicable in the control group. The modified protocol, which included prolonged etching and re-infiltration, showed greater penetration depth, higher lesion volume coverage, and lower residual porosity than the standard protocol. Three-dimensional analysis demonstrated that infiltration was most pronounced in the superficial and central lesion zones, with lower but consistent penetration in deeper regions. Our study supports the effectiveness of resin infiltration as a microinvasive strategy for early enamel lesion management and suggests that protocol modification may enhance infiltrant distribution within demineralized enamel.

Keywords: white spot lesions, resin infiltration, ICON, micro-computed tomography, enamel demineralization, minimally invasive dentistry.

Introduction

White spot lesions (WSLs) represent an early stage of enamel demineralization, characterized by subsurface mineral loss beneath a relatively intact superficial layer. Their clinical significance extends beyond the initial carious process itself, because these lesions also produce visible esthetic alterations, especially on anterior teeth and in patients after orthodontic treatment. Due to the increased porosity of the enamel, light scattering is modified, generating the typical opaque white appearance that frequently becomes a major reason for presentation and treatment request [1]. In our study, this pathologic and esthetic duality is particularly relevant, as WSLs are not only biologically active lesions but also clinically important defects requiring tissue-preserving management. Current therapeutic concepts increasingly favor

minimally invasive strategies intended to arrest lesion progression while preserving sound dental structure [2].

Resin infiltration has emerged as one of the most relevant microinvasive approaches for the management of non-cavitated enamel lesions. The technique is based on the penetration of a low-viscosity resin into the porous body of the lesion by capillary action, with subsequent polymerization creating a barrier that limits acid diffusion and may reduce further demineralization. In addition to this preventive effect, resin infiltration has major esthetic implications, since the infiltrant may modify the refractive properties of the lesion and reduce the visual contrast between demineralized and sound enamel [3]. In our study, this dual mechanism, structural penetration and optical improvement, forms the conceptual basis for evaluating infiltration efficacy in artificial WSLs. Previous investigations have already shown that resin infiltration can improve the appearance of post-orthodontic WSLs, a setting in which esthetic concerns are often considerable after bracket removal [4].

Clinical evidence has further supported the value of ICON-based infiltration in the management of WSLs. Durable esthetic improvement has been demonstrated in treated lesions when compared with no therapy, including split-mouth randomized clinical designs with follow-up evaluation [5]. Additional randomized clinical data have shown that minimally invasive resin infiltration may represent an effective therapeutic alternative for arrested white spot lesions, supporting its clinical applicability beyond purely theoretical assumptions [6]. In our study, these findings justify the experimental interest in understanding not only whether ICON is effective, but also how effectively the infiltrant penetrates lesion structure under different application protocols.

Imaging methods play a central role in this context. Previous studies have used optical coherence tomography to visualize resin infiltration within non-cavitated lesions, highlighting the importance of assessing internal lesion occupation rather than relying exclusively on surface appearance [7]. In our study, micro-computed tomography (micro-CT) was selected because it enables three-dimensional, non-destructive evaluation of lesion morphology, infiltrant distribution, and volumetric changes. Recent *in vitro* micro-CT evidence has shown that resin infiltration may inhibit the progression of early lesions and improve structural lesion parameters, further supporting this methodological approach [8]. Moreover, resin infiltration has been compared with microabrasion, remineralization protocols, and fluoride-based strategies, with several reports indicating favorable esthetic and therapeutic outcomes for infiltration under selected conditions [9-13].

The broader literature also supports the long-term effectiveness of infiltration-based management. Randomized clinical trials on proximal lesions have demonstrated significant efficacy after three-year and seven-year follow-up periods, suggesting that infiltration may provide stable lesion control over time [14,15]. In our study, we build on this evidence by focusing specifically on the three-dimensional penetration behavior of ICON within artificially induced enamel lesions and by comparing the standard protocol with a modified protocol involving prolonged etching and re-infiltration.

Materials and Methods

Study design and sample preparation

In our study, we performed an *in vitro* experimental investigation designed to evaluate the effect of resin infiltration using ICON (DMG, Hamburg, Germany) on artificially induced

white spot lesions by means of micro-computed tomography (micro-CT). We included a total of 60 extracted human teeth, which were randomly allocated into three experimental groups (n = 20 per group): control, ICON standard protocol, and ICON modified protocol. We selected sound teeth free of visible cracks, structural defects, carious lesions, restorations, or developmental abnormalities. Before experimental manipulation, all teeth were cleaned and prepared under standardized conditions. To obtain a uniform experimental substrate, only teeth with preserved enamel surfaces suitable for controlled demineralization and subsequent micro-CT evaluation were included.

Artificial lesion formation

In our study, we induced artificial white spot lesions under controlled laboratory conditions in order to obtain a standardized demineralized enamel model. The specimens were exposed to a demineralizing protocol designed to create subsurface enamel lesions while preserving the superficial enamel layer. After lesion formation, all specimens underwent baseline micro-CT assessment to confirm lesion presence and to quantify the initial lesion parameters before treatment.

The baseline micro-CT analysis included lesion depth, lesion volume, mineral density reduction, and initial porosity. Only specimens showing clearly defined and measurable subsurface lesions were retained for further analysis.

Resin infiltration protocol

We divided the specimens into three groups according to the treatment protocol. The control group did not receive resin infiltration. In the ICON standard group, we applied the infiltration protocol according to the manufacturer's recommendations. In the ICON modified protocol group, we used a protocol that included prolonged etching and re-infiltration to assess whether enhanced surface conditioning and repeated application improved resin penetration and lesion coverage.

For the treated groups, the enamel surfaces were conditioned, dried, and infiltrated using ICON resin infiltrant (DMG, Hamburg, Germany) under standardized experimental conditions. After application, excess material was removed and the infiltrant was light-cured according to the protocol used in each group.

Micro-CT analysis

Micro-computed tomography (micro-CT) was used to evaluate lesion morphology at baseline in all specimens and resin distribution after treatment in the ICON-treated groups. Scanning was performed under standardized acquisition settings, followed by three-dimensional reconstruction for volumetric and regional assessment. In all groups, baseline lesion characteristics included lesion depth, lesion volume, mineral density reduction, and initial porosity. After treatment, post-intervention micro-CT analysis focused on penetration depth, percentage of infiltrated lesion volume, residual porosity, and lesion volume reduction. Because no infiltrant was applied in the control group, resin-dependent variables such as penetration depth, percentage of infiltrated lesion volume, and lesion volume reduction were considered not applicable for biological measurement and were therefore recorded as not applicable (NA).

Outcome measures

The primary outcome was the extent of resin penetration into the artificial enamel lesion, assessed as penetration depth and percentage of infiltrated lesion volume in the treated groups. Secondary outcomes included residual porosity, lesion volume reduction, and the regional distribution of infiltrant resin within the superficial, central, and deep lesion zones. In the control group, no resin-dependent infiltration variables could be biologically detected because no infiltrant was applied; therefore, these parameters were recorded as not applicable (NA) and were analyzed only in the ICON-treated groups when appropriate.

Statistical analysis

We performed the statistical analysis using IBM SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean \pm standard deviation (SD). Comparisons among the three groups were performed using one-way analysis of variance (ANOVA) for normally distributed variables. When appropriate, post hoc comparisons were performed to identify intergroup differences. For all statistical analyses, we considered a p-value < 0.05 to indicate statistical significance.

Results

Baseline characteristics and micro-CT lesion parameters

A total of 60 enamel specimens with artificially induced white spot lesions were analyzed using micro-computed tomography (micro-CT). The specimens were randomly allocated into three groups (n = 20 per group) according to the planned experimental protocols. Baseline micro-CT assessment showed comparable lesion characteristics across the three groups before treatment. No statistically significant differences were observed in lesion depth, lesion volume, mineral density reduction, or initial porosity (p > 0.05 for all comparisons). These findings confirmed the homogeneity of the experimental model and the comparability of the baseline lesion parameters among groups. The baseline micro-CT characteristics are summarized in Table 1.

Table 1. Baseline micro-CT characteristics of artificial enamel lesions.

Parameter	Control (n = 20)	ICON Standard (n = 20)	ICON Modified Protocol (n = 20)	p-value
Lesion depth (μm), mean \pm SD	146.3 \pm 28.4	149.7 \pm 30.1	151.5 \pm 27.9	0.73
Lesion volume (mm^3), mean \pm SD	0.184 \pm 0.041	0.191 \pm 0.046	0.188 \pm 0.043	0.82
Mineral density reduction (%), mean \pm SD	32.6 \pm 6.3	33.4 \pm 5.9	34.1 \pm 6.1	0.64
Initial porosity (%), mean \pm SD	21.3 \pm 4.5	22.1 \pm 4.2	21.7 \pm 4.6	0.71

Data are presented as mean \pm standard deviation (SD). Baseline micro-CT measurements showed no significant differences among groups.

Effect of ICON infiltration on lesion penetration and porosity reduction

Micro-CT analysis demonstrated substantial penetration of the infiltrant resin into the artificial enamel lesions following ICON treatment. As expected, no resin penetration was

identified in the untreated control group, in which no infiltrant had been applied; accordingly, resin-dependent infiltration variables were considered not applicable in this group. Penetration depth was substantial in both ICON-treated groups and was significantly greater in the modified protocol group than in the standard protocol group (Table 2). The standard ICON protocol achieved infiltration of approximately two-thirds of the lesion depth, whereas the modified protocol, which included prolonged etching and re-infiltration, produced slightly higher penetration values. A marked reduction in lesion porosity was also observed after resin infiltration, with significantly lower residual porosity in treated specimens compared with the untreated control group ($p < 0.001$). Lesion volume reduction values further suggested partial structural stabilization of the demineralized enamel after treatment, with higher reduction values in the modified protocol group than in the standard protocol group (Table 2). Collectively, these findings support the ability of resin infiltration to penetrate the porous enamel network and reduce lesion porosity.

Table 2. Micro-CT quantitative analysis of lesion penetration and porosity reduction following ICON infiltration.

Parameter	Control (n = 20)	ICON Standard (n = 20)	ICON Modified Protocol (n = 20)	p-value
Penetration depth (μm), mean \pm SD	NA	102.4 \pm 24.7	118.6 \pm 27.3	0.04
Percentage of infiltrated lesion (%), mean \pm SD	NA	68.9 \pm 12.5	76.3 \pm 13.1	0.03
Residual porosity (%), mean \pm SD	21.5 \pm 4.8	11.2 \pm 3.7	9.6 \pm 3.1	<0.001
Lesion volume reduction (%), mean \pm SD	NA	38.4 \pm 9.5	44.7 \pm 10.2	0.04

NA: not applicable, as no infiltrant was applied in the control group. For penetration depth, percentage of infiltrated lesion, and lesion volume reduction, p-values refer to comparisons between the two ICON-treated groups only. Residual porosity was compared across all three groups.

3.3. Three-dimensional micro-CT morphological analysis of resin infiltration

Three-dimensional micro-CT reconstruction enabled detailed evaluation of the spatial distribution of the infiltrant resin within the artificial enamel lesions. In the ICON-treated specimens, the infiltrant occupied a substantial proportion of the porous enamel structure and extended from the superficial lesion zone toward the deeper lesion body. The modified ICON protocol showed higher infiltration values and a more homogeneous distribution within the lesion volume than the standard protocol. Regional analysis demonstrated that infiltration was greatest in the superficial and central lesion zones, whereas lower penetration values were recorded in the deep lesion zone adjacent to sound enamel. Despite this gradient, the infiltrant consistently occupied most of the lesion microporosities, indicating effective occlusion of the demineralized enamel network. The regional three-dimensional micro-CT findings are summarized in Table 3, and a representative reconstruction is shown in Figure 1.

Table 3. Regional three-dimensional micro-CT analysis of resin infiltration depth within artificial enamel lesions.

Lesion Region	ICON Standard (n = 20)	ICON Modified Protocol (n = 20)	p-value
Superficial lesion zone (μm), mean \pm SD	118.4 \pm 26.5	134.7 \pm 28.2	0.02
Central lesion zone (μm), mean \pm SD	103.2 \pm 24.1	120.6 \pm 25.4	0.01
Deep lesion zone (μm), mean \pm SD	86.7 \pm 20.3	98.4 \pm 22.7	0.04
Overall infiltrated lesion volume (%), mean \pm SD	69.1 \pm 11.8	77.5 \pm 12.4	0.01

Data are presented as mean \pm standard deviation (SD). Three-dimensional analysis demonstrated significantly greater infiltration depth and lesion volume coverage in the modified ICON protocol.

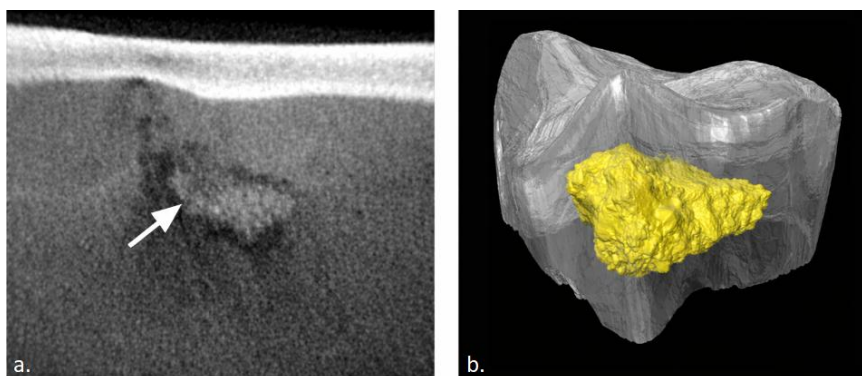


Figure 1. Three-dimensional micro-CT reconstruction illustrates resin infiltration within artificial enamel lesions following ICON treatment. (a) Cross-sectional micro-CT image showing penetration of the infiltrant resin into the porous enamel lesion. (b) Three-dimensional reconstruction showing the spatial distribution of infiltrated resin within the lesion body.

Discussion

White spot lesions represent a clinically relevant manifestation of early enamel demineralization and remain an important focus of minimally invasive dentistry. The management of these lesions aims not only to halt the progression of the demineralization process but also to improve the esthetic appearance of affected enamel surfaces. In our study, micro-computed tomography analysis demonstrated that resin infiltration using ICON achieved substantial penetration within artificially induced enamel lesions and significantly reduced lesion porosity. These findings support the concept that infiltration can occupy the microporous network of demineralized enamel and contribute to structural stabilization of the lesion body.

The rationale for resin infiltration is based on the presence of subsurface porosities that develop during the early stages of enamel demineralization. These microporosities allow diffusion of acids and dissolved minerals, facilitating lesion progression if the process remains uncontrolled. Resin infiltration introduces a low-viscosity resin capable of penetrating these porous pathways through capillary forces, thereby creating a diffusion barrier that restricts further acid penetration and potentially arrests lesion progression [1-3]. In our study, the

observed infiltration depths and lesion occupation percentages confirm that the infiltrant effectively penetrated the lesion body and filled a substantial portion of the porous enamel structure.

Previous clinical and experimental investigations have demonstrated that resin infiltration can improve both the structural and esthetic characteristics of white spot lesions. Studies evaluating post-orthodontic lesions have reported noticeable esthetic improvements following ICON treatment, with durable results observed during follow-up periods extending several months after therapy [4,5]. In addition, randomized clinical trials have indicated that minimally invasive infiltration may represent a clinically effective treatment option for arrested white spot lesions, supporting its use as an alternative to more invasive restorative procedures [6]. In our study, the micro-CT findings provide structural evidence that complements these clinical observations, showing that infiltration extends throughout a significant portion of the lesion depth.

Advanced imaging methods have contributed significantly to understanding the behavior of infiltrant materials within enamel lesions. Optical coherence tomography and other imaging techniques have demonstrated that resin can penetrate subsurface lesions and distribute along enamel porosities [7]. In our study, micro-CT was selected because it enables high-resolution three-dimensional evaluation of lesion morphology and infiltrant distribution without destructive sectioning. This approach allowed quantitative analysis of parameters such as penetration depth, residual porosity, and lesion volume reduction. Similar experimental investigations using micro-CT have confirmed that resin infiltration can inhibit lesion progression and modify lesion structure in early carious lesions [8].

Another important observation in our study was the difference between the standard ICON protocol and the modified protocol involving prolonged etching and re-infiltration. The modified protocol produced greater penetration depth and higher percentages of infiltrated lesion volume, suggesting that enhanced surface conditioning may improve the accessibility of lesion microporosities. These findings are consistent with the concept that surface layer removal and improved lesion permeability can facilitate deeper resin penetration. Previous studies comparing infiltration with other minimally invasive approaches, such as microabrasion or remineralization therapies, have reported variable outcomes depending on lesion structure and treatment protocol [9-13]. Our results suggest that protocol optimization may play an important role in maximizing infiltration efficiency.

Long-term clinical studies have also supported the effectiveness of resin infiltration in preventing lesion progression. Randomized clinical trials evaluating proximal caries lesions have demonstrated sustained efficacy over follow-up periods of three and even seven years, indicating that infiltration may provide durable lesion control in clinical settings [14-17]. Although our study was conducted under *in vitro* conditions, the structural findings obtained through micro-CT analysis align with these clinical observations and support the mechanism through which infiltration may stabilize early lesions.

Despite these promising findings, several limitations should be acknowledged. In our study, artificial lesions were created under controlled laboratory conditions, which may not fully replicate the complexity of natural caries lesions. Natural lesions often present heterogeneous mineral distribution and structural variability that could influence infiltration

behavior. In addition, the experimental model did not account for biological factors such as saliva, biofilm activity, or cyclic demineralization-remineralization processes that occur in the oral environment. Furthermore, although micro-CT provides detailed structural information, it cannot directly evaluate clinical parameters such as long-term esthetic stability or resistance to further cariogenic challenges.

Within these limitations, our study provides valuable three-dimensional evidence regarding the penetration behavior of ICON resin infiltration within artificial enamel lesions. The findings suggest that resin infiltration can effectively occupy lesion microporosities and significantly reduce lesion porosity, while modified protocols involving enhanced surface conditioning may further improve infiltration depth and lesion coverage. Future investigations should combine micro-CT structural analysis with long-term clinical evaluation in order to better understand the relationship between infiltration depth, lesion stabilization, and clinical outcomes.

Conclusions

Our study demonstrated that ICON resin infiltration achieved substantial penetration within artificially induced white spot lesions and significantly reduced lesion porosity, supporting its effectiveness as a microinvasive approach for early enamel lesion management. Micro-CT analysis confirmed that the infiltrant occupied a considerable proportion of the lesion body, indicating that resin infiltration may contribute to structural stabilization of demineralized enamel while preserving sound dental tissue. Our study also showed that the modified infiltration protocol, which included prolonged etching and re-infiltration, resulted in greater penetration depth and more homogeneous lesion coverage than the standard protocol. These findings suggest that protocol optimization may enhance the three-dimensional distribution of infiltrant resin within enamel lesions. Although the experimental design was limited to an in vitro model, the results provide relevant structural evidence supporting the use of resin infiltration in the management of early non-cavitated lesions and justify further clinical studies to confirm long-term therapeutic and esthetic outcomes.

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