Journal of Dentistry 159 (2025) 105853

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

Comparative evaluation of ICON resin infiltration and bioactive glass adhesive for managing initial caries lesions using quantitative light-induced fluorescence: a randomized clinical trial

Zakereyya S.M. Albashaireh [a,*], Susan N. Al-Khateeb [b], Malak K. Altallaq [a]

[a] Department of Conservative Dentistry, Faculty of Dentistry, Jordan University of Science and Technology, Irbid, 22110, Jordan
[b] Department of Preventive Dentistry, Faculty of Dentistry, Jordan University of Science and Technology, Irbid, 22110, Jordan

ARTICLE INFO

Keywords:
White spot lesion
Initial caries lesion
Icon Infiltrant
HI Bond Universal
Remineralization
Light-induced fluorescence (QLF)

ABSTRACT

Introduction: Various approaches have been developed for the treatment of initial caries lesions (ICLs). ICON resin infiltrant is considered the gold standard for its superior aesthetic recovery; however, it is relatively expensive. Hi-Bond Universal is a bioactive glass adhesive that may promote remineralization and serve as a cost-effective alternative treatment.

Aim: This clinical trial compared the efficacy of Hi-Bond Universal and ICON in improving the aesthetic appearance of ICLs assessed by quantitative light-induced fluorescence (QLF).

Methods: A split-mouth design was used, with ICLs in two different quadrants of each participant. One quadrant was treated with ICON resin infiltration following the manufacturer's instructions, while the other received the bioactive glass adhesive. QLF imaging was performed at baseline (T0) and one-month post-treatment (T1) to assess remineralization. Three parameters were measured: lesion area, fluorescence loss (ΔF), and the deepest point of the lesion (ΔFmax).

Results: Both materials showed statistically significant improvement in QLF parameters (ΔF, ΔFmax, and lesion area) from baseline T0 to T1 ($p < 0.001$). The mean changes in ΔF, ΔFmax, and lesion area were -5.34 and -13.30, -589.06 px^2 respectively for the Hi-Bond group, compared to -6.34, -15.12, -586.22 px^2 for ICON group. No significant difference was proven between the two groups ($p > 0.05$).

Conclusions: Both the bioactive glass adhesive Hi-Bond Universal and the resin infiltration ICON effectively promoted the aesthetic recovery of ICLs for over one month. Hi-Bond Universal may serve as a viable alternative to ICON, particularly in cases where cost is a limiting factor.

Clinical Significance: This study suggests that Hi-Bond Universal, a bioactive glass adhesive, offers similar efficacy to ICON resin infiltration in managing ICLs. Given its lower cost, Hi-Bond Universal may provide a practical and effective alternative in routine clinical settings, especially where affordability is a concern.

1. Introduction

The initial clinical manifestation of a carious lesion typically appears as an ICL, resulting from an imbalance between the processes of demineralization and remineralization within the enamel surface. ICLs are also referred to as incipient lesion, subsurface lesion, white spot lesion, or early caries lesion [1]. The term "white spot lesion" refers to areas of subsurface enamel porosity that represent as a milky-white opacity on smooth surfaces [2–4]. While "white spot lesion" remains favored in clinical settings for its descriptive appearance, the term "initial caries lesion" is considered more precise, better reflecting the early substance changes within the enamel, as recognized in cariology literature [5].

The ICL is characterized by a loss of minerals beneath the intact enamel surface. The mineral loss alters the refractive index (RI) of the affected enamel. Light passing through the enamel surface is scattered by the subsurface demineralized area, producing the characteristic opaque, white appearance [3].

The global prevalence of dental caries is high, affecting 46.2 % of primary teeth and 53.8 % of permanent teeth [6]. The occurrence of ICLs is common among orthodontic patients. A meta-analysis reported an incidence rate of 45.8 % and a prevalence rate of 68.4 % during fixed

* Corresponding author.
E-mail address: albashai@just.edu.jo (Z.S.M. Albashaireh).

https://doi.org/10.1016/j.jdent.2025.105853
Received 13 April 2025; Received in revised form 21 May 2025; Accepted 25 May 2025
Available online 27 May 2025

orthodontic treatment [7]. Existing oral hygiene status and the presence of lesions before treatment are significant prognostic factors for ICL development [8]. Based on post-orthodontic treatment evaluations using QLF, up to 97 % of individuals with fixed appliances may experience ICLs [9,10].

While ICLs may undergo some spontaneous remineralization, complete aesthetic recovery is not guaranteed. The most significant improvement in appearance occurs shortly following orthodontic appliance removal [11]. However, ICLs may persist and even progress, potentially developing into cavities if left untreated [12].

There are multiple options for treatment of ICL, ranging from conservative to invasive techniques. These can be categorized into four main approaches: the remineralization strategies [1], micro-invasive techniques [13,14], minimally invasive techniques and more invasive methods like composite restorations [4,15].

The remineralization approach involves high-concentration topical fluoride applications [16]. Fluoride varnishes and bioactive glass have been proven effective in arresting ICL progression [17]. However, aesthetic improvements may be limited, since high fluoride concentrations primarily promote remineralization of the superficial enamel layer while the underlying subsurface layer remains susceptible to continuous demineralization [15,18,19].

The micro-invasive technique is a management approach in which synthetic resin penetrates and fills the microporosities of the lesion [13]. ICON resin stands out as an innovative material specially designed for micro-invasive management of ICL, eliminating the need for drilling. It blends effectively with surrounding enamel, providing a significant aesthetic benefit [13,20].

Despite its clinical success and recognition as the gold standard for ICL infiltration, ICON's high cost can be prohibitive, particularly for patients requiring treatment of multiple lesions. This makes it less accessible, especially in cases where dental insurance does not cover the procedure.

Bioactive materials have emerged as a cost-effective and biologically beneficial alternative. Hi-Bond Universal (MDCLUS, Cheongju-si, South Korea), a novel bioactive universal adhesive, contains mesoporous bioactive glass, specifically the nanofiller (Bioglass 45S5), which releases calcium, phosphate, and fluoride into the oral environment. These ions penetrate hard tooth tissues, inhibit demineralization, contribute to enamel remineralization, and support the repair of carious tissue [21]. Additionally, Hi-Bond Universal incorporates the functional monomer 10-MDP, which promotes chemical bonding to tooth structure and provides continuous pH buffering [22]. Its Bio-regeneration properties further suggest that Hi-Bond Universal may not only seal ICLs but also support remineralization and repair of demineralized enamel and dentine [21].

Bioactive glass-containing resin composite has been tested and proven effective in dentinal tubule remineralization [23]. However, clinical evidence evaluating its in vivo remineralization potential and impact on ICL management remains lacking. Therefore, this clinical trial was designed to compare the efficacy of Hi-Bond Universal bioactive glass resin adhesive and ICON resin infiltration for improving the aesthetic appearance of ICLs, as assessed by QLF.

The null hypothesis of this study was that Hi-Bond Universal bioactive adhesive would not result in a statistically significant difference in fluorescence loss parameters of ICLs, as measured by QLF, over one month compared to ICON resin infiltrant.

2. Material and methods

2.1. Ethical approval and recruitment of patients

Ethical approval for this clinical trial was obtained from the Institutional Review Board (IRB) (IRB 35/160/2023). This research was funded from the deanship of research [Grant number 20,230,339]. Additionally, the trial was officially registered on ClinicalTrials.gov under the reference number NCT06402500.

Participants signed a written informed consent form prior to the initiation of the restorative clinical procedures. Fifteen patients were recruited for this trial, each presenting with at least one ICL on the labial surface of teeth in two contralateral quadrants, both requiring treatments.

Patients were included if they were post-orthodontic and had obvious areas of ICLs on the labial surfaces of maxillary or mandibular anterior teeth and premolars. The exclusion criteria included cavitated lesions requiring restoration, environmental or developmental enamel defects, existing restorations on affected teeth, diabetes mellitus or metabolic conditions, pregnancy, and smoking.

2.2. Study design and sample size calculation

This randomized clinical trial followed a split-mouth design wherein each participant received the two treatments on different sides of the mouth. It was conducted at the Postgraduate Clinics of Restorative Dentistry, during the period February 2024 to December 2024. The number of participants, allocation of teeth to each treatment group, and the final numbers of restorations evaluated at the one-month recall visit are presented in a CONSORT flow diagram (Fig. 1). The CONSORT reporting guidelines have been used during the preparation of this report [24].

The required sample size was calculated using GPower Software (Version 3.1.9.7) (developed by Heinrich-Heine University Düsseldorf, Germany) based on an expected effect size of 0.45, with a significance level of α=0.05 and a power of 95 %. The degrees of freedom (DF) for the outcomes were calculated as: $(5 - 1) \times (2 - 1) = 4$ resulting in a critical chi-square ($\chi 2$) value of 9.49.

Using these parameters, the required sample size of each group was determined to be 46 lesions, resulting in a total of 92 lesions across both groups. To account for potential dropouts or missing data, an additional

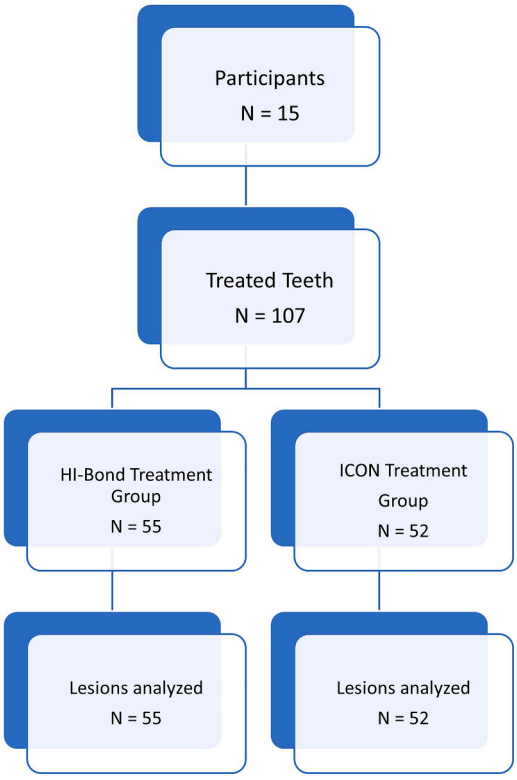

Fig. 1. CONSORT flow diagram showing the number of participants, treated teeth, and lesions allocated to the ICON and Hi-Bond Universal treatment groups.

10 % was added yielding a total of 102 lesions (51 teeth per quadrant).

2.3. Randomization and blinding

The randomization process ensured that each participant received both treatments (HI Bond and ICON) on different sides of the mouth. A total of 102 ICLs were randomly assigned to one of the two treatment protocols using a computer-generated randomization list, created with online software (www.sealedenvelope.com). Patients were blinded to the details of the experiment and were unaware of which side of the mouth was treated with which material.

2.4. Inclusion and exclusion criteria

Patients were included if they had post-orthodontic ICLs on the labial surfaces of maxillary or mandibular anterior teeth and premolars, had completed orthodontic treatment at least one month prior to enrollment, and provided written informed consent.

Exclusion criteria included cavitated lesions requiring restoration, environmental or developmental enamel defects, existing restorations on affected teeth, diabetes mellitus or other metabolic conditions, pregnancy and smoking.

2.5. Treatment protocols

After the clinical examination, teeth with visible ICLs were recorded using Palmer notation system. The dental arch was divided into two quadrants: one quadrant received treatment with the resin infiltration material (ICON DMG, Hamburg, Germany), while the other quadrant was treated with the bioactive glass adhesive material Hi-Bond Universal (MDCLUS, Cheongju-si, South Korea). The Icon Resin Infiltrant system includes Icon Etch, Icon Dry, and Icon Infiltrant. Hi-Bond Universal contains mesoporous bioactive glass (MBG), a methacrylate polymer-based resin, and ethanol. The composition details of both treatment materials are provided in Table 1.

Treatment allocation was assigned irrespective of the number of teeth in each quadrant. Orthodontic patients were enrolled in the study no earlier than one month and no later than three months after debonding of their fixed orthodontic appliances [25]. Scaling was performed when indicated, especially if the patient had not undergone scaling in the last three months. Treatment commenced one week after scaling to ensure gingival health. Preoperative baseline records were captured using a QLF device.

Table 1
Composition and manufacturers of the tested resin materials.

Material	Composition*	Manufacturer
HI-Bond UNIVERSAL	• Methacrylate polymer-based resin • Ethanol • Mesoporous bioactive glass (MBG)	MDCLUS, Cheongju-si, South Korea
ICON Resin Infiltrant	• Icon Etch ingredients: • Water • Hydrochloric acid • Bioactive dental glass • Additives • Icon Dry ingredients: • Ethanol • Water • Icon Infiltrant ingredients: • TEGDMA, • TMPEOTA, • Additives, • 2-ethylhexyl 4-dimethylaminobenzoate	DMG, Hamburg, Germany

* According to the product information provided in the manufacturer's leaflet.

2.6. Restorative procedures

Both materials were applied according to the manufacturer's instructions using a standardized protocol (Fig. 2). After isolating the tooth with a rubber dam (Step 1) the enamel surface was polished with a blue rubber polishing cup, then thoroughly rinsed with water and air-dried (Step 2).

Lesions were etched with Icon-Etch (15 % hydrochloric acid) for two minutes with gentle agitation, rinsed with water for 30 s, and air-dried for 10 s (Step 3). Icon-Dry (ethanol >99 %) was then applied for 30 s and air-dried for 10 s (Step 4). If a frosty appearance of the enamel surface was not observed after the initial etching, a second etching step was performed for 60 s followed by a water rinse for 30 s and air drying (Step 5).

For resin application, either Icon or Hi-Bond Universal infiltrant was applied and left undisturbed for 3 min (Step 6). The lesion surface was kept wet throughout this time by intermittently twisting the Icon syringe for the Icon group, or by intermittently dabbing the surface with a microbrush dipped in resin. Resin was then dispersed with air, and floss was used interproximally before light curing was performed for 40 s using an LED curing light (D-Light Pro, 1200 mW/cm^2) (Step 6). A second application was performed for 60 s, followed by air dispersion and a final 40-second light polymerization (Step 7). The treated surfaces were polished with a rubber polishing cup for 10 s and rinsed with water (Step 8).

The same overall protocol was applied to both groups to ensure procedural consistency and minimize bias. A schematic summary of the entire restorative procedure is provided in Fig. 2.

2.7. Clinical evaluation

Follow-up assessments were performed one month after treatment and included QLF imaging to monitor changes in ICLs. All lesion assessments were performed by the same clinician who carried out the treatments. A QLF-D Biluminator™ 2 (Inspektor Research Systems BV, Amsterdam, Netherlands) was used for fluorescence imaging. This system consists of the Canon 450D full-sensor single-lens reflex (SLR) camera equipped with BiluminatorTM, containing blue and white LEDs arranged around the lens aperture. The tube includes differential filtering, allowing for both regular and fluorescent imaging. Photo capture was controlled via dedicated software on a PC [26].

To ensure reproducibility, the camera cone remained in direct contact with patient's cheek, maintaining a constant imaging distance. Fluorescence images of the teeth with ICLs were captured before the application of the adhesive (T0) and after one month of follow-up (T1).

2.8. Measured variables

The following lesion parameters were analyzed:

1. Fluorescence loss (ΔF %) – indicating mineral loss within the lesion.
2. Maximum fluorescence loss (ΔFmax %) – representing the deepest point of mineral loss.
3. Lesion surface area (px^2) – measured in pixels

2.9. Lesion analysis and quantification

Fluorescence loss and lesion area were quantified using dedicated software (QA2 version 1.18, Inspektor Research B.V., Amsterdam, Netherlands). To determine lesion extent, a patch was drawn around the lesion site, ensuring its borders align with sound enamel. Within this patch, the fluorescence levels of affected enamel were reconstructed based on the fluorescence radiance of the surrounding sound enamel. The percentage difference between the reconstructed fluorescence levels and the original fluorescence levels was then calculated [27].

To determine lesion surface area, contour points were used to outline

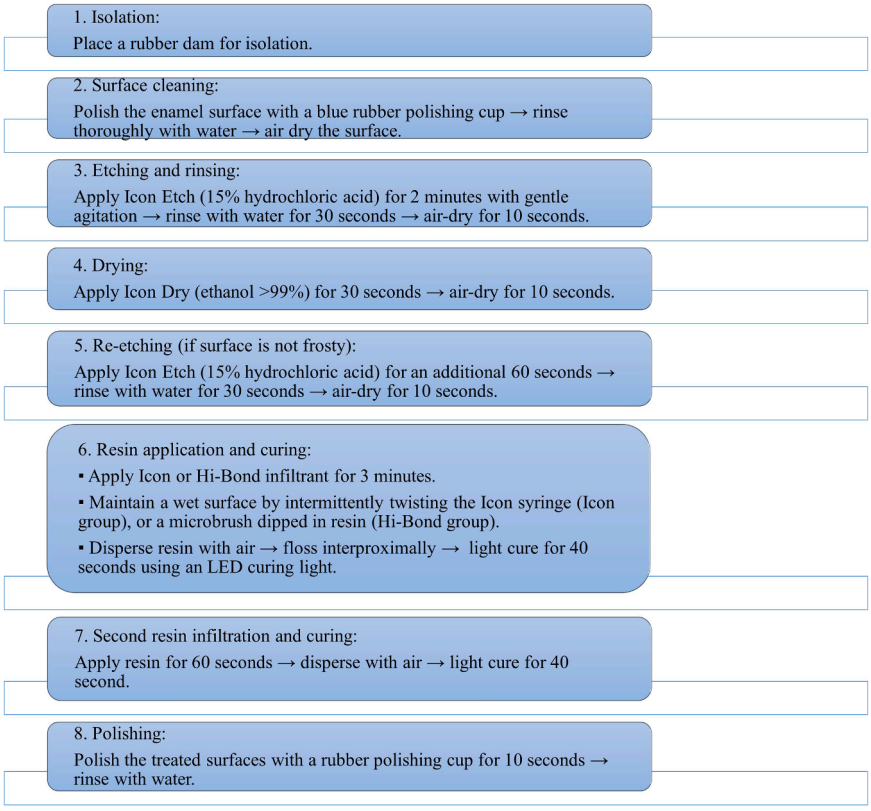

Fig. 2. Step-by-step schematic illustration of the resin infiltration procedure used for both ICON and Hi-Bond Universal groups.

the lesion in pixels^2. Decalcification was visually assessed in QLF images, appearing as dark areas surrounded by brightly fluorescing sound enamel. The measured values were recorded in an Excel spreadsheet for statistical comparison between pre-and post-treatment data.

2.10. Statistical methods

Data was analyzed using IBM SPSS Statistics (Version 28, IBM Corp., Armonk, NY, USA). Data normality was assessed using Kolmogorov-Smirnov test. Consequently, non-parametric tests were used to verify possible differences. The Mann-Whitney U test was used to compare ΔF, ΔFmax, and ICL area between the two treatment groups. Within each group, the pairs of data before and after treatment were tested using the Wilcoxon Signed Ranks test. Additionally, the change in F (ΔF), Fmax (ΔFmax) and ICL Area (ΔWS Area) were calculated for each patient. Statistical significance was set at $P < 0.05$.

3. Results

3.1. Descriptive statistics

A total of 107 teeth with ICLs from fifteen patients were included in this study. Of these, fifty-five teeth were treated using the bioactive glass adhesive and fifty-two teeth treated with the resin infiltration material. The difference in numbers occurred because some patients had an unequal number of eligible lesions between contralateral quadrants.

3.2. Comparative statistics

The results of both groups were analyzed separately within each group by comparing baseline (T0) and one- month follow-up (T1) measurements (Table 2). Both groups demonstrated significant improvement in ΔF, ΔFmax, and lesion surface area from baseline to the one-month follow-up ($p < 0.001$). Figs. 3 and 4 show representative QLF images from the ICON and Hi-Bond groups, respectively, visually illustrating changes in lesion characteristics from baseline (T0; Fig. 3) to the one-month follow-up (T1; Fig. 4).

Table 2
Mean and standard deviation (SD) of fluorescence loss (ΔF, ΔFmax) and lesion area before and after treatment with Hi-Bond Universal and ICON.

Parameter	Hi-Bond Universal (Mean ± SD)	ICON (Mean ± SD)	p-value (b)
ΔF (T0) (Lesion fluorescence loss before treatment)	−9.84 ± 6.70	−9.36 ± 7.23	0.948
ΔF (T1) (Lesion fluorescence loss after treatment)	−4.51 ± 6.32	−3.20 ± 5.32	0.922
p-value (a)	<0.001	<0.001	—
ΔFmax (T0) (Maximum lesion fluorescence loss before treatment)	−22.61 ± 21.51	−21.42 ± 19.38	0.579
ΔFmax (T1) (Maximum lesion fluorescence loss after treatment)	−9.31 ± 16.90	−6.73 ± 14.36	0.246
p-value (a)	<0.001	<0.001	—
Lesion area (T0) (Lesion surface area before treatment, px^2)	931.50 ± 1448.75	857.94 ± 1127.16	0.286
Lesion area (T1) (Lesion surface area after treatment, px^2)	342.44 ± 1236.09	288.55 ± 837.97	0.400
p-value (a)	<0.001	<0.001	—

p-value (a): Within-group significance of change from T0 to T1.
p-value (b): Between-group comparison at each time point.

The mean changes in ΔF, ΔFmax, and lesion surface area from baseline to follow-up were −5.34, −13.30, and −589.06 px^2 for the Hi-Bond group, compared to −6.34, −15.12, and −586.22 px^2 for the ICON group, respectively (Table 3). To further assess the differences in the lesion size between the two treatment groups, the changes in lesion measurements from baseline (T0) to one-month follow-up (T1) were

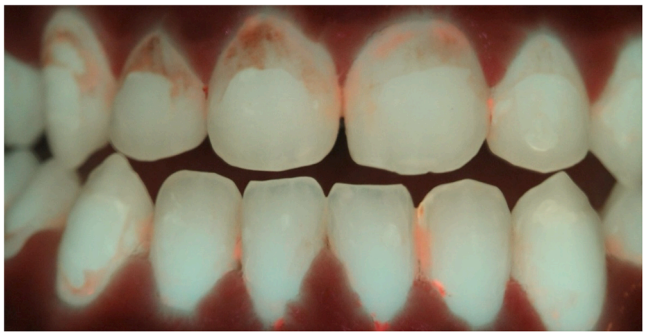

Fig. 3. Representative QLF image of initial caries lesions at baseline (T0).
The maxillary right quadrant shows QLF images of the right canine, lateral incisor, and central incisor prior to treatment with ICON resin infiltrate, while the left quadrant shows the central and lateral incisors before treatment with Hi-Bond Universal. The image illustrates baseline fluorescence and lesion visibility prior to the application of either treatment.

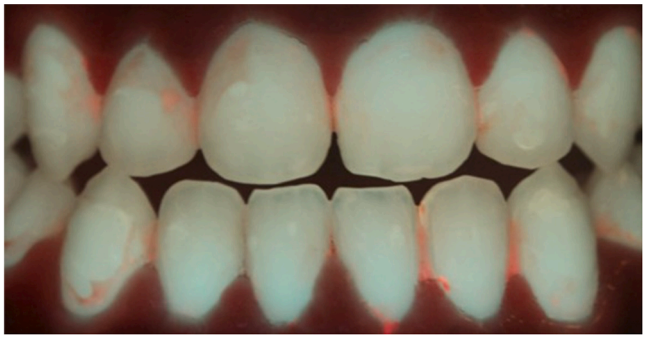

Fig. 4. Representative QLF image of initial caries lesions at one-month follow-up (T1).
The maxillary right quadrant shows the right canine, lateral incisors, and central incisors one month after treatment with ICON resin infiltrate, while the left quadrant shows the central and lateral incisors one month after treatment with Hi-Bond Universal. The image illustrates changes in fluorescence and lesion visibility following treatment.

Table 3
Mean change (± SD) in QLF parameters from baseline (T0) to one-month follow-up (T1) for both treatment groups.

Parameter	Hi-Bond Universal (Mean ± SD)	ICON (Mean ± SD)	p-value
ΔF (Lesion fluorescence loss)	−5.34 ± 6.01	−6.34 ± 6.05	0.111
ΔFmax (Maximum lesion fluorescence loss)	−13.30 ± 16.12	−15.12 ± 14.21	0.264
ΔICL Area (Reduction in lesion surface area, px^2)	−589.06 ± 1073.22	−586.22 ± 1056.05	0.492

calculated and compared. Intergroup comparisons showed no statistically significant differences between Hi-Bond Universal and ICON in the mean changes of ΔF, ΔFmax, or lesion surface area ($p > 0.05$) (Table 3).

4. Discussion

The null hypothesis of this study was that Hi-Bond Universal bioactive adhesive would not produce a statistically significant difference in fluorescence loss parameters of ICLs, as assessed by QLF, over one month compared to ICON resin infiltrant. This hypothesis was rejected, as no significant difference was found between the two materials in terms of fluorescence loss measurements.

Although the study aimed to assign an equal number of lesions to each treatment group on contralateral jaw sides per patient, the final distribution of treated teeth was slightly imbalanced between groups. This occurred because some patients presented with an unequal number of eligible lesions across contralateral quadrants. For ethical reasons, all identified lesions were treated, resulting in 55 teeth in the ICON group and 52 teeth in the Hi-Bond Universal group.

Patients with certain systemic conditions known to affect salivary composition and flow, such as metabolic disorders, diabetes, pregnancy, and smoking [26–28] were excluded to minimize confounding variables. This is particularly relevant for Hi-Bond Universal, wherein its bioactivity relies on its interaction with salivary electrolytes and salivary flow [29,30].

QLF was used in this study due to its non-invasive, reproducible nature, providing a reliable tool for measuring subtle changes in ICL fluorescence, which are typically associated with alterations in the mineral content of enamel. before and after the treatment. This allowed for objective, quantitative monitoring of lesion behavior over time [31, 32].

The results of this clinical trial demonstrated that both Hi-Bond Universal and ICON contributed to a reduction in fluorescence loss (ΔF, ΔFMax) and lesion surface area, as measured by QLF, indicating an improvement in the appearance of ICLs. Several studies affirmed that changes in these parameters could be due to mineral gain in the ICL [25, 26,33]. In the Hi-Bond treatment group, the enhanced color match is likely due to combined effects of resin infiltration and mineral gain facilitated by the bioactive properties of the material. In contrast, the improvement observed with ICON treatment is more plausibly due to optical masking from resin infiltration alone, as lesion remineralization is unlikely following complete sealing [13].

The bioactive material incorporated in Hi-Bond Universal is based on 45S5 bioactive glass, a composition well recognized for its ability to promote enamel remineralization and support caries management [21, 34]. Upon exposure to moisture, 45S5 bioactive glass undergoes ion exchange, releasing calcium, phosphate, sodium, and other beneficial ions into the surrounding environment. This ionic release not only increases the local pH, creating a less acidic, antibacterial environment, but also facilitates the precipitation of a hydroxycarbonate apatite (HCA)-like layer that mimics the natural mineral content of enamel and promotes filling of porosities within subsurface lesions [21]. This dual action, remineralization and pH modulation, is particularly advantageous for managing ICLs, where mineral restoration within the lesion body is critical [34].

The mechanism of action of 45S5 glass in Hi-Bond closely aligns with other bioactive systems. Fluoride-containing bioactive materials, such as BioMinF® and similar glass-based sealers, promote re mineralization through the sustained release of calcium, phosphate, and fluoride ions, leading to the formation of fluorapatite, which enhances acid resistance [35]. In contrast, borate-based bioactive glasses demonstrate more rapid degradation and ions release, which may enhance antibacterial efficacy but can compromise the long-term mineral stability needed in adhesive applications [21]. These characteristics suggest that the 45S5 bioactive glass in Hi-Bond offers an effective balance between remineralization capacity, biocompatibility, and structural durability in managing ICLs [34].

The current study revealed that there are no significant intergroup differences in the aesthetic appearance of ICLs after one month, suggesting that both materials provided comparable visual improvement. While this does not directly confirm the bioactive effect of Hi-Bond Universal, its performance comparable to ICON supports its potential as a cost-effective alternative. Moreover, the results are consistent with previous studies showing that ICON can effectively arrest ICL progression [31,36,37].

Another factor to consider is the potential influence of the Hawthorne effect wherein participants may alter their behavior or the outcomes of a study due to awareness of being observed. This factor could have contributed to the observed improvements in both treatment

groups [38].

QLF was used in this study as a non-invasive and reproducible method to assess changes in lesion fluorescence, which are typically associated with alterations in the mineral content of enamel. However, it is important to note that QLF may not reliably distinguish between fluorescence changes caused by actual remineralization and those due to the resin infiltration [31,32].

QLF technology measures changes in fluorescence that generally reflect alterations in mineral content of enamel. However, following resin infiltration, the improvement in fluorescence readings may partly result from optical masking due to the infiltration of resin into the porous lesion body rather than true mineral gain.

The masking ability of the infiltration stems from its refractive index (RI). The low-viscosity resin used in micro-invasive infiltration has RI (1.475), similar to that of sound enamel (1.65). This similarity enables the resin to mask the white spot appearance of ICLS by altering light transmission through the lesion [39]. Because QLF utilizes the refraction of light from the surface, the fluorescence difference of the ICL as compared to adjacent sound enamel decreases following infiltration, potentially mimicking remineralization [40]. Consequently, while QLF remains a valuable tool for monitoring lesion changes, its results following resin-based interventions must be interpreted with caution [40]. In the present study, the observed reductions in ΔF, ΔFmax, and lesion area in both treatment groups likely reflect a combination of true remineralization in the Hi-Bond Universal group, due to its bioactive properties and optical masking in the ICON group.

4.1. Study limitations and future research

The split-mouth design used in this study may have introduced a risk of ionic cross-contamination between quadrants, potentially influencing the remineralization process observed in Hi-Bond Universal treated lesions. However, as ICON acts primarily through resin infiltration and lesion sealing, cross-contamination would likely have had minimal effect on its outcomes. Future studies using a parallel-group design are recommended to better isolate material-specific effects.

Additionally, the absence of a fluoride-only control group limits the ability to directly compare the tested materials with conventional remineralization strategies. A fluoride control group is planned for an upcoming study to address this limitation.

Finally, while QLF provided a sensitive, non-invasive assessment of lesion changes, it cannot distinguish between true mineral gain and optical masking by resin infiltration. Complementary methods, such as scanning electron microscopy or microradiography, could provide deeper insights into enamel microstructure and help validate the long-term efficacy of bioactive glass materials.

5. Conclusions

Hi-Bond Universal bioactive resin and ICON resin infiltrant both improved the clinical appearance of ICLs, as assessed by QLF. Given their comparable effectiveness, Hi-Bond Universal presents a promising and cost-effective alternative to ICON for managing ICLs. Long-term clinical studies with extended follow-up are warranted to assess the sustainability of these improvements over time..

CRediT authorship contribution statement

Zakereyya S.M. Albashaireh: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Susan N. Al-Khateeb:** Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Malak K. Altallaq:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Acknowledgements

This study was supported by deanship of research, Jordan university of science and technology, Irbid, Jordan, grant number: 20230339.

References

[1] Z. Xie, L. Yu, S. Li, J. Li, Y. Liu, Comparison of therapies of white spot lesions: a systematic review and network meta-analysis, BMC Oral Health 23 (1) (2023) 346.
[2] H. Milly, F. Festy, T.F. Watson, I. Thompson, A. Banerjee, Enamel white spot lesions can remineralise using bio-active glass and polyacrylic acid-modified bio-active glass powders, J. Dent. 42 (2) (2014) 158–166.
[3] K.B. Roopa, S. Pathak, P. Poornima, I.E. Neena, White spot lesions: a literature review, J. Pediatr. Dent. 3 (1) (2015) 1–7.
[4] D. Al-Blaihed, O. El Meligy, K. Baghlaf, R.A. Aljawi, S. Abudawood, White spot lesions in fixed orthodontics: a literature review on etiology, prevention, and treatment, Cureus 16 (7) (2024) e65679.
[5] V. Machiulskiene, G. Campus, J.C. Carvalho, I. Dige, K.R. Ekstrand, A. Jablonski-Momeni, M. Maltz, D.J. Manton, S. Martignon, E.A. Martinez-Mier, N.B. Pitts, A. G. Schulte, C.H. Splieth, L.M.A. Tenuta, A. Ferreira Zandona, B. Nyvad, Terminology of dental caries and dental caries management: consensus report of a workshop organized by ORCA and Cariology Research Group of IADR, Caries Res. 54 (1) (2020) 7–14.
[6] M. Kazeminia, A. Abdi, S. Shohaimi, R. Jalali, A. Vaisi-Raygani, N. Salari, M. Mohammadi, Dental caries in primary and permanent teeth in children's worldwide, 1995 to 2019: a systematic review and meta-analysis, Head Face Med. 16 (1) (2020) 22.
[7] D. Sundararaj, S. Venkatachalapathy, A. Tandon, A. Pereira, Critical evaluation of incidence and prevalence of white spot lesions during fixed orthodontic appliance treatment: a meta-analysis, J. Int. Soc. Prev. Community Dent. 5 (6) (2015) 433–439.
[8] W. Lu, N. Wang, X. Fang, H. Yang, H. He, D. Qin, F. Hua, Prognostic factors and prognostic models for white spot lesions: a systematic review and meta-analysis, J. Dent. 156 (2025) 105686.
[9] K.C. Julien, P.H. Buschang, P.M. Campbell, Prevalence of white spot lesion formation during orthodontic treatment, Angle Orthod. 83 (4) (2013) 641–647.
[10] J.G. Boersma, M.H. van der Veen, M.D. Lagerweij, B. Bokhout, B. Prahl-Andersen, Caries prevalence measured with QLF after treatment with fixed orthodontic appliances: influencing factors, Caries Res. 39 (1) (2005) 41–47.
[11] S. Kim, M. Katchooi, B. Bayiri, M. Sarikaya, A.M. Korpak, G.J. Huang, Predicting improvement of postorthodontic white spot lesions, Am. J. Orthod. Dentofacial Orthop. 149 (5) (2016) 625–633.
[12] S.E. Bishara, A.W. Ostby, White spot lesions: formation, prevention, and treatment, Semin. Orthod. 14 (3) (2008) 174–182.
[13] H. Askar, J. Lausch, C.E. Dörfer, H. Meyer-Lueckel, S. Paris, Penetration of micro-filled infiltrant resins into artificial caries lesions, J. Dent. 43 (7) (2015) 832–838.
[14] S.V. Senestraro, J.J. Crowe, M. Wang, A. Vo, G. Huang, J. Ferracane, D. A. Covell Jr., Minimally invasive resin infiltration of arrested white-spot lesions: a randomized clinical trial, J. Am. Dent. Assoc. 144 (9) (2013) 997–1005.
[15] H. Yuan, J. Li, L. Chen, L. Cheng, R.D. Cannon, L. Mei, Esthetic comparison of white-spot lesion treatment modalities using spectrometry and fluorescence, Angle Orthod. 84 (2) (2014) 343–349.
[16] M. Sugiura, Y. Kitasako, A. Sadr, Y. Shimada, Y. Sumi, J. Tagami, White spot lesion remineralization by sugar-free chewing gum containing bio-available calcium and fluoride: a double-blind randomized controlled trial, J. Dent. 54 (2016) 86–91.
[17] A.A. Taha, M.P. Patel, R.G. Hill, P.S. Fleming, The effect of bioactive glasses on enamel remineralization: a systematic review, J. Dent. 67 (2017) 9–17.
[18] F. Schwendicke, J.E. Frencken, L. Bjorndal, M. Maltz, D.J. Manton, D. Ricketts, K. Van Landuyt, A. Banerjee, G. Campus, S. Domejean, M. Fontana, S. Leal, E. Lo, V. Machiulskiene, A. Schulte, C. Splieth, A.F. Zandona, N.P. Innes, Managing carious lesions: consensus recommendations on carious tissue removal, Adv. Dent. Res. 28 (2) (2016) 58–67.
[19] D.R. Willmot, White lesions after orthodontic treatment: does low fluoride make a difference? J. Orthod. 31 (3) (2004) 235–242, discussion 202.
[20] G.S. Araujo, F.S. Naufel, R.C. Alonso, D.A. Lima, R.M. Puppin-Rontani, Influence of staining solution and bleaching on color stability of resin used for caries infiltration, Oper. Dent. 40 (6) (2015) E250–E256.
[21] L.L. Dai, M.L. Mei, C.H. Chu, E.C.M. Lo, Mechanisms of bioactive glass on caries management: a review, Materials (Basel) 12 (24) (2019) 4183.
[22] E. Carrilho, M. Cardoso, M.M. Ferreira, C.M. Marto, A. Paula, A.S. Coelho, 10-MDP based dental adhesives: adhesive interface characterization and adhesive stability-A systematic review, Materials (Basel) 12 (5) (2019) 790.
[23] J.H. Jang, M.G. Lee, J.L. Ferracane, H. Davis, H.E. Bae, D. Choi, D.S. Kim, Effect of bioactive glass-containing resin composite on dentin remineralization, J. Dent. 75 (2018) 58–64.

[24] K.F. Schulz, D.G. Altman, D. Moher, C. Group, CONSORT 2010 statement: updated guidelines for reporting parallel group randomised trials, BMC Med. 8 (2010) 18.
[25] S. Al-Khateeb, C.M. Forsberg, E. de Josselin de Jong, B. Angmar-Mansson, A longitudinal laser fluorescence study of white spot lesions in orthodontic patients, Am. J. Orthod. Dentofacial Orthop. 113 (6) (1998) 595–602.
[26] M.R. Alammari, P.W. Smith, E. de Josselin de Jong, S.M. Higham, Quantitative light-induced fluorescence (QLF): a tool for early occlusal dental caries detection and supporting decision making in vivo, J. Dent. 41 (2) (2013) 127–132.
[27] G.R.M. La Rosa, E. Pedullà, I. Chapple, S.A. Pacino, R. Polosa, The use of quantitative light-induced fluorescence in carious lesions research: a bibliometric review, J. Dent. 148 (2024) 105220.
[28] L.M. Silverstone, Operative measures for caries prevention, Caries Res. 12 (Suppl 1) (1978) 103–112.
[29] M.A. Abbassy, A.S. Bakry, E.H. Almoabady, S.M. Almusally, A.H. Hassan, Characterization of a novel enamel sealer for bioactive remineralization of white spot lesions, J. Dent. 109 (2021) 103663.
[30] F.J. Dowd, Saliva and dental caries, Dent. Clin. North Am. 43 (4) (1999) 579–597.
[31] S. Paris, W. Hopfenmuller, H. Meyer-Lueckel, Resin infiltration of caries lesions: an efficacy randomized trial, J. Dent. Res. 89 (8) (2010) 823–826.
[32] Y.S. Song, Y. Choi, M.J. Lim, M.K. Yu, C.U. Hong, K.W. Lee, K.S. Min, In vitro evaluation of a newly produced resin-based endodontic sealer, Restor. Dent. Endod. 41 (3) (2016) 189–195.
[33] B. Angmar-Mansson, J.J. ten Bosch, Quantitative light-induced fluorescence (QLF): a method for assessment of incipient caries lesions, Dentomaxillofac. Radiol. 30 (6) (2001) 298–307.
[34] O.L. Zhang, J.Y. Niu, I.X. Yin, O.Y. Yu, M.L. Mei, C.H. Chu, Bioactive Materials for Caries Management: a literature review, Dent. J. (Basel) 11 (3) (2023) 59.
[35] A.S. Bakry, M.A. Abbassy, H.F. Alharkan, S. Basuhail, K. Al-Ghamdi, R. Hill, A novel fluoride containing bioactive glass paste is capable of re-mineralizing early caries lesions, Materials (Basel) 11 (9) (2018) 1636.
[36] A.B. Borges, T.M. Caneppele, D. Masterson, L.C. Maia, Is resin infiltration an effective esthetic treatment for enamel development defects and white spot lesions? A systematic review, J. Dent. 56 (2017) 11–18.
[37] S.M. Hammad, M. El Banna, I. El Zayat, M.A. Mohsen, Effect of resin infiltration on white spot lesions after debonding orthodontic brackets, Am. J. Dent. 25 (1) (2012) 3–8.
[38] J. McCambridge, J. Witton, D.R. Elbourne, Systematic review of the Hawthorne effect: new concepts are needed to study research participation effects, J. Clin. Epidemiol. 67 (3) (2014) 267–277.
[39] Y.L. Sezici, H. Cinarcik, E. Yetkiner, R. Attin, Low-viscosity resin infiltration efficacy on postorthodontic white spot lesions: a quantitative light-induced fluorescence evaluation, Turk. J. Orthod. 33 (2) (2020) 92–97.
[40] I. Knaup, C. Kobbe, E.E. Ehrlich, M. Esteves-Oliveira, B. Abou-Ayash, H. Meyer-Lueckel, M. Wolf, R.J. Wierichs, Correlation of quantitative light-induced fluorescence and qualitative visual rating in infiltrated post-orthodontic white spot lesions, Eur. J. Orthod. 45 (2) (2023) 133–141.