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Resin Infiltration Versus Fluoride-Based Therapies in the Management of White Spot Lesions, with Relevance to Athletes and Sports Dentistry: A Narrative Review

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Abstract

Background: White spot lesions (WSLs) are the most common esthetic complication of fixed orthodontic treatment, resulting from subsurface enamel demineralization around brackets. Athletes are a recognized high-risk group, in whom acidic sports drinks and exercise-related hyposalivation promote demineralization, linking WSL care to sports dentistry. Fluoride-based therapies (FBT) remain standard for prevention but poorly mask established lesions, whereas resin infiltration (RI) optically camouflages WSLs by refractive index matching. **Aim:** To compare the efficacy, esthetic outcomes, durability and safety of RI and FBT in post-orthodontic WSLs and outline evidence-based recommendations. **Materials and Methods:** A narrative review used PubMed, Scopus and Google Scholar, including trials, reviews, meta-analyses and clinical and in vitro studies (2014–2025). **Results:** RI provided superior immediate and short-term masking versus fluoride varnish, with significantly greater reductions in colour difference (ΔE) stable up to four years. FBT (5% NaF varnish, CPP-ACP) arrested lesions and promoted remineralization but poorly resolved discoloration. **Conclusions:** RI is the most predictable option for immediate esthetic management of post-orthodontic WSLs, while FBT remains essential for prevention and biological stabilization; a combined sequential strategy appears most effective, particularly in physically active patients. Long-term randomized trials with standardized outcomes are needed.

Key words: white spot lesions; resin infiltration; fluoride varnish; CPP-ACP; orthodontic treatment; enamel demineralization; athletes; sports dentistry

1. Introduction

White spot lesions (WSLs) are clinically defined as opaque, milky-white areas of enamel resulting from subsurface demineralization, representing the earliest macroscopically visible stage of the carious process.[1,2] In orthodontic patients, WSLs typically develop adjacent to fixed appliances, where prolonged plaque retention disturbs the equilibrium between demineralization and remineralization at the enamel surface.[1,3] The reported prevalence of post-orthodontic WSLs varies widely depending on diagnostic methodology and patient demographics, with epidemiological studies indicating substantial increases in WSL frequency over the course of fixed appliance therapy.[1,4] The reported prevalence varies widely, from 11.6% in survey data to up to 97% in clinical detection, with adolescent males being the most affected group.[5]

The pathogenesis of WSLs is multifactorial. Cariogenic biofilms dominated by *Streptococcus mutans* and *Lactobacillus* species accumulate around brackets, ligatures, and bands, fermenting dietary carbohydrates into organic acids that diffuse through the enamel surface and dissolve the underlying mineral phase.[1,3] The result is a porous subsurface lesion covered by a relatively well-mineralized surface layer. The increased porosity alters the refractive index of the enamel, producing the characteristic chalky white appearance and a marked optical contrast with the adjacent sound enamel.[6,7] The optical mechanism behind this whitish appearance is well established: sound enamel, dominated by hydroxyapatite, has a refractive index of approximately 1.62, whereas the microporosities created by demineralisation are filled with water (refractive index ≈ 1.33) or air (refractive index ≈ 1.0). The marked mismatch between these refractive indices forces light to traverse multiple optical interfaces inside the lesion, producing increased internal scattering and the chalky-white appearance characteristic of WSLs.[8] Risk factors include suboptimal oral hygiene, frequent intake of fermentable carbohydrates, low salivary flow, prolonged duration of orthodontic treatment, and appliance design.[1,2]

Certain populations are at particularly elevated risk of enamel demineralization. Athletes and physically active individuals are increasingly recognized as one such group: frequent intake of acidic and sugar-rich sports, energy and isotonic drinks, combined with exercise-induced hyposalivation, dehydration and mouth breathing during exertion, can reduce the salivary buffering capacity that normally protects against demineralization, and epidemiological data report a high prevalence of dental erosion and caries among athletes.[50,51] Although the evidence linking sports drinks alone to erosion remains inconclusive, the overall risk profile is

multifactorial and clinically relevant, with swimmers and endurance athletes appearing especially susceptible.[52] When young athletes additionally undergo fixed multibracket treatment, these factors may compound the already elevated risk of post-orthodontic WSL formation around brackets, making the effective esthetic and biological management of established lesions directly relevant to sports and exercise medicine.

Accurate diagnosis and assessment of lesion activity are crucial for treatment selection. Clinical examination is commonly supplemented by the International Caries Detection and Assessment System (ICDAS), laser fluorescence (DIAGNOdent), quantitative light-induced fluorescence (QLF), and digital spectrophotometry, which allow objective quantification of lesion size, mineral content, and color change (ΔE).[2,9] These diagnostic modalities are increasingly used in clinical trials to provide reproducible esthetic and biological outcome measures.

From an esthetic perspective, post-orthodontic WSLs can substantially compromise patient satisfaction with the outcome of treatment intended to improve dental appearance, particularly when anterior teeth are affected.[1,2,10] Importantly, dental caries is a preventable condition and its progression can be halted at the WSL stage, which is why fluoride-based protocols have long been the cornerstone of routine caries management; they enable conservative, often restoration-free care and help to break the cycle of repeated restorative intervention.[11] Even after debonding, when oral hygiene typically improves and superficial remineralisation may occur, the visual outcome with adjunctive fluoride therapy alone often remains esthetically unsatisfactory.[10] Although fluoride-based therapies (FBT) – including topical varnishes, dentifrices, and rinses – remain the foundation of caries prevention and lesion arrest, their clinical effectiveness depends on the maintenance of adequate intraoral fluoride levels and therefore on continuous, compliant use, which has motivated investigation of complementary approaches such as resin infiltration, lasers and other emerging technologies.[3,12,13] Resin infiltration (RI) is a micro-invasive technique developed and commercialized as Icon (DMG, Hamburg, Germany), which combines erosion of the hypermineralized surface layer with infiltration of a low-viscosity TEGDMA-based resin into the lesion body.[6,14] By restoring a refractive index close to that of healthy enamel, RI produces an immediate and clinically perceptible improvement in esthetics.

This review aims to provide an updated comparative overview of resin infiltration and fluoride-based therapies in the management of post-orthodontic WSLs, focusing on their mechanisms of action, clinical efficacy, long-term outcomes, and current role within minimally invasive contemporary dentistry.

2. Materials and Methods

A narrative review of the literature was conducted using the PubMed/MEDLINE database, with additional searches in Scopus and Google Scholar to identify relevant articles not indexed in PubMed. The search strategy combined the following keywords and Medical Subject Headings (MeSH terms): ("white spot lesion" OR "WSL" OR "enamel demineralization" OR "post-orthodontic decalcification") AND ("resin infiltration" OR "Icon" OR "caries infiltration") AND ("fluoride" OR "fluoride varnish" OR "casein phosphopeptide" OR "CPP-ACP") AND ("orthodontic*").

Inclusion criteria comprised: (1) randomized controlled trials, prospective and retrospective clinical studies, systematic reviews, meta-analyses, and high-quality narrative reviews; (2) studies focusing on post-orthodontic WSLs in permanent dentition; (3) articles published between January 2014 and January 2025; (4) full-text availability in English. Exclusion criteria included case reports without comparator groups, studies on primary dentition, in vitro studies without clinical correlation, and articles unrelated to esthetic or biological outcomes of RI or FBT.

After screening titles and abstracts, full-text articles were reviewed for relevance and quality. Reference lists of selected articles and previous reviews were also screened to identify additional sources. The final reference list reflects the most clinically relevant and methodologically robust evidence available within the defined search period.

3. Fluoride-Based Therapies

Fluoride-based therapies have long been considered the cornerstone of non-invasive management of WSLs in orthodontic patients.[1,3,12] Used in dentistry for more than seven decades, fluoride is widely regarded as the single most important factor underlying the global decline in caries prevalence, acting on both the inorganic and microbial components of the carious process.[8] On the mineral side, fluoride deposits a calcium fluoride–like layer on the enamel surface that serves as a labile reservoir and supports the formation of fluorapatite, a phase markedly less soluble than hydroxyapatite under acidic conditions.[8] The resulting fluorapatite crystals exhibit greater resistance to acid dissolution than native hydroxyapatite, decreasing the critical pH at which demineralization occurs and shifting the dynamic equilibrium toward remineralization.[1,12] On the microbial side, fluoride interferes with the metabolism of cariogenic biofilms — particularly through inhibition of bacterial enolase and other glycolytic enzymes — reducing acid production, modulating plaque composition and,

especially at low intraoral concentrations, favouring the remineralisation of incipient lesions.[1,15]

A wide range of fluoride delivery vehicles is currently available, including 5% sodium fluoride (NaF) varnishes (e.g., Duraphat, Flairesse), high-concentration fluoride dentifrices (1450–5000 ppm), gels, and mouth rinses. Among these, 5% NaF varnish is widely regarded as the gold standard for prevention of new lesions and arrest of active WSLs in orthodontic patients.[1,3] Topical fluoride application is generally well tolerated, inexpensive, and easily incorporated into routine recall visits, and surveys of general dental practice confirm that topical fluoride remains among the most commonly applied preventive measures during multibracket appliance treatment.[16] Both systematic and narrative reviews have shown that topical fluoride formulations — varnishes, gels and toothpastes — and fluoride-releasing bonding materials can reduce the severity of WSL formation around fixed appliances, and clinical data indicate that 0.2% NaF rinsing and the daily use of high-fluoride dentifrices significantly lower the prevalence and incidence of new lesions next to brackets during orthodontic treatment.[17] Consistent with this, a Cochrane review found that, in patients wearing fixed orthodontic appliances, daily use of a 5000 ppm fluoride toothpaste throughout treatment may reduce the number of patients developing new demineralised lesions when compared with a conventional 1450 ppm fluoride toothpaste.[18] A randomised controlled trial further demonstrated that a low-dose amine fluoride (Amflor) mouthwash used over a six-month period of fixed orthodontic therapy produced significantly lower WSL scores on maxillary incisors and premolars than a standard regimen relying on fluoridated toothpaste alone, supporting the role of adjunctive fluoride rinses in compliant orthodontic patients.[17] Beyond home-use products, professional fluoride prophylaxis with varnish or gel is recommended in patients identified as being at increased caries risk, since in-office application is independent of domestic compliance and ensures controlled delivery; a meta-analysis of 36 randomised trials reported NaF varnish to be the most effective single agent against orthodontically induced WSLs, and varnish reapplied at every orthodontic appointment has been shown to reduce enamel demineralisation by approximately 44 % compared with placebo.[19]

Bioactive remineralizing agents based on casein phosphopeptide–amorphous calcium phosphate (CPP-ACP) have been developed to deliver bioavailable calcium and phosphate ions to the enamel surface, supporting subsurface mineral gain.[20,21] Products containing CPP-ACP (Tooth Mousse) and CPP-ACP combined with fluoride (CPP-ACPF, MI Paste Plus) have been investigated as adjuncts or alternatives to conventional fluoride therapy. A systematic review

of randomized clinical trials by Imani et al. concluded that both CPP-ACP and CPP-ACPF can decrease the prevalence and increase the remineralization of WSLs in orthodontic patients, although results regarding superiority of either formulation were inconsistent across included studies.[20] A randomized clinical trial by Singh et al. comparing fluoride toothpaste alone, fluoride toothpaste with fluoride varnish, and fluoride toothpaste with CPP-ACP crème in the management of post-orthodontic WSLs demonstrated remineralization in all groups.[21]

Despite their well-established preventive role, fluoride-based therapies have important limitations in the post-orthodontic esthetic context. Remineralization induced by topical fluoride agents tends to occur predominantly within the outermost layer of the lesion, leaving the deeper porous body largely unaffected and visually persistent.[3,22] In the multicenter randomized clinical trial by Kashash et al., topical fluoride varnish (Flairesse) applied during multibracket treatment did not produce a clinically relevant change in the color difference (ΔE) between WSLs and adjacent sound enamel over a six-month observation period, in marked contrast to the resin infiltration group.[23]Moreover, the time required to achieve appreciable optical improvement with fluoride therapy is typically several months and depends heavily on patient compliance with oral hygiene and dietary recommendations.

4. Resin Infiltration Technique

Resin infiltration is a micro-invasive treatment originally developed to arrest non-cavitated proximal carious lesions and subsequently expanded to manage smooth-surface WSLs of carious and non-carious origin, including post-orthodontic decalcifications and developmental defects of enamel.[6,14] The technique is intended to bridge the therapeutic gap between purely non-invasive remineralization and traditional restorative intervention.[14] Among the currently available modalities for managing orthodontically induced WSLs, resin infiltration has consistently emerged as one of the most effective treatment options, offering both immediate esthetic improvement and arrest of lesion progression in a single clinical session.[24] Clinical reports of post-orthodontic WSLs on maxillary anterior teeth have demonstrated marked optical improvement and high patient satisfaction following Icon infiltration, with patients reporting significant reduction in the visibility of lesions and a positive impact on their perception of treatment outcome.[25] A contemporary review of WSL development and treatment further underscores the suitability of resin infiltration as a microinvasive intervention across a range of clinical indications in orthodontic patients, highlighting its well-defined mechanism, predictable esthetic results and favourable safety profile.[26]In vitro evidence confirms that resin infiltration is an effective method of halting the progression of non-cavitated proximal lesions

extending radiographically up to the outer third of dentine, outperforming non-operative measures used alone in terms of caries arrest.[27]

The clinical protocol with the most widely studied commercial system (Icon, DMG, Hamburg, Germany) consists of three principal steps. First, the lesion surface is etched with 15% hydrochloric acid (HCl) gel for approximately two minutes, removing the relatively well-mineralized hypermineralized surface layer that would otherwise impede infiltration.[6,12,14] The use of HCl gel has been shown to be superior to conventional 37% phosphoric acid in removing the surface layer, producing approximately twice the penetration depth and enabling access to the deeper portions of the lesion.[28] Second, the lesion is desiccated with 99% ethanol, which displaces water from the porosities and prepares them for infiltration; this step simultaneously reduces the viscosity and contact angle of the subsequently applied resin, thereby increasing its penetration coefficient.[14,28]Finally, a low-viscosity, triethylene glycol dimethacrylate (TEGDMA)-based resin infiltrant is applied for approximately three minutes, drawn into the porous enamel by capillary action, and subsequently light-cured.[6,14]

The masking effect achieved by RI is based on optical principles. Sound enamel has a refractive index of approximately 1.62–1.65, while air-filled porosities within demineralized lesions have a refractive index of 1.0, producing pronounced light scattering and the characteristic milky-white appearance.[6,14] Once the porosities are filled with a polymerized TEGDMA-based resin, with a refractive index close to that of healthy enamel, the optical interface between sound and demineralized enamel is largely abolished, allowing the lesion to blend chromatically with the surrounding tissue – an effect frequently described as a "chameleon" or camouflage effect.[6,14,29]Beyond the esthetic improvement, the infiltrated resin seals the enamel porosities against acid diffusion, thereby arresting lesion progression and simultaneously reinforcing the demineralised tissue against further cariogenic challenge, which restores enamel structural integrity while concealing the characteristic opaque appearance.[30]

Penetration depth of the resin is a key determinant of clinical success. The systematic review and meta-analysis by Soveral et al. demonstrated that resin infiltration significantly improves enamel surface roughness and microhardness, with substantial penetration into the body of the WSL.[9] A dedicated systematic review further confirmed that resin infiltration achieves superior penetration depth compared with fissure sealants, CPP-ACP, flowable composites, dental adhesives and fluoride varnish, and that this depth of penetration is a critical determinant of the effectiveness of the diffusion barrier formed within the lesion.[31] Beyond its esthetic role, RI mechanically stabilizes the porous enamel structure and obstructs the diffusion pathways for

cariogenic acids, thereby contributing to lesion arrest.[6,9] A network meta-analysis of randomised controlled trials confirmed that the capacity of resin infiltration to penetrate and occlude porous enamel, preventing acid diffusion and halting lesion progression, underpins its dual preventive and esthetic function, making it a particularly valuable option in the early management of WSLs during active orthodontic treatment.[32]

5. Comparative Clinical Efficacy: RI versus FBT

A growing body of randomized controlled trials and systematic reviews has directly compared resin infiltration with fluoride-based therapies in the treatment of post-orthodontic WSLs, with consistent findings favoring RI for esthetic outcomes.[22,23,33] Resin infiltration has been shown to produce a significantly higher masking effect than natural remineralization or regular application of fluoride varnishes, and is considered an effective, relatively non-invasive approach with clear advantages over other available options for treating WSLs.[34]

In the multicenter, two-arm randomized clinical trial by Kashash et al., 36 adolescent patients (116 teeth) with WSLs (ICDAS 1–2) developing during fixed multibracket treatment were assigned to receive either resin infiltration with Icon or fluoride varnish (Flairesse). Standardized digital photographs and color analysis demonstrated a statistically significant reduction in color difference (ΔE) in the RI group (ΔE at baseline 8.81 ± 2.17 to ΔE at one day 5.01 ± 1.45; $p < 0.001$), which remained stable at the six-month follow-up (5.2 ± 1.6). In contrast, the fluoride group showed no clinically meaningful improvement in lesion-to-enamel color difference over the same observation period.[23] A randomised clinical trial in a paediatric population further confirmed that resin infiltration achieved significantly greater reduction in ΔE compared with fluoride varnish both immediately after treatment and at follow-up, with the RI group demonstrating consistently lower colorimetric values throughout the observation period.[35]

These findings are consistent with the systematic review and meta-analysis by Bourouni et al., which evaluated eleven studies (1834 teeth in 413 patients) comparing RI with untreated controls and with fluoride varnish. Resin infiltration was associated with significantly greater optical improvement compared to both untreated controls and topical fluoride therapy, while showing comparable safety and arresting capacity.[22] A network meta-analysis by Xie et al. comparing multiple WSL therapies (RI, fluoride varnish, CPP-ACP, CPP-ACFP, and self-assembling peptide P11-4) further supported the favorable position of RI for esthetic outcomes, while highlighting the role of remineralizing agents in lesion arrest.[33] A systematic review and meta-analysis specifically examining the effect of resin infiltration on the color and brightness

of post-orthodontic WSLs found significant and clinically relevant improvements in both parameters six months after treatment, with color stability maintained across the included studies for up to 24 months and no adverse effects reported.[36]

Importantly, both treatment modalities are effective in arresting the progression of demineralization. The biological component of RI – the mechanical sealing of porosities – combined with continued use of fluoride dentifrices and good oral hygiene, results in lesion arrest comparable to that achieved with FBT alone.[9,22] Adjunctive use of CPP-ACP or self-assembling peptide P11-4 has been suggested to further enhance subsurface remineralization, particularly in deeper or more active lesions.[20,33,37]

A summary of representative comparative clinical studies is presented in Table 1.

Table 1. Summary of selected clinical studies comparing resin infiltration and fluoride-based therapies in the management of WSLs.

Study (year)	**Design**	**Population / Lesions**	**Intervention vs Comparator**	**Main Outcome**
Kashash et al. (2024)[23]	Multicenter RCT, parallel-group	36 patients, 116 teeth, age 12–17 (ICDAS 1–2 during MBA)	Resin infiltration (Icon) vs fluoride varnish (Flairesse)	Significant ΔE reduction with RI (8.8→5.0; p<0.001), stable at 6 months; no significant change with fluoride
Bourouni et al. (2021)[22]	Systematic review and meta-analysis	11 studies, 1834 teeth in 413 patients	RI vs untreated; RI vs fluoride varnish	RI significantly superior optical improvement vs untreated and vs fluoride varnish

Xie et al. (2023)[33]	Systematic review and network meta-analysis	Multiple RCTs on WSL therapies	RI vs fluoride varnish vs CPP-ACP vs SAP P11-4	RI most effective for esthetic masking; remineralizing agents most effective for lesion arrest
Singh et al. (2016)[21]	RCT (45 subjects)	Post-orthodontic WSLs, age 16–25	Fluoride toothpaste alone vs + fluoride varnish vs + CPP-ACP	All groups improved DIAGNOdent values; CPP-ACP showed most pronounced remineralization
Brescia et al. (2022)[7]	Retrospective clinical study	33 patients with developmental enamel defects (incl. post-traumatic, MIH, mild fluorosis)	Resin infiltration (Icon)	Esthetic improvement maintained at 24 months in all cases
Puleio et al. (2023)[38]	Prospective clinical study	40 non-cavitated WSLs	Resin infiltration (Icon)	Significant ΔE reduction at T1 ($p<0.05$); stable at 1 and 4 years

Abbreviations: ΔE, color difference; ICDAS, International Caries Detection and Assessment System; MBA, multibracket appliance; MIH, molar–incisor hypomineralization; RCT, randomized controlled trial; RI, resin infiltration; WSL, white spot lesion.

6. Long-Term Outcomes: Color Stability, Durability and Mechanical Properties

Long-term performance is a critical consideration when evaluating any esthetic dental intervention. Several prospective and retrospective studies have demonstrated favorable durability of the masking effect achieved by resin infiltration. The systematic review by Saccucci et al. on color stability of resin infiltration in human teeth identified twelve clinical studies and concluded that infiltrated lesions remained chromatically stable, with no clinically significant color drift over follow-up periods extending up to several years.[39] A systematic review by Abang Ibrahim et al. similarly confirmed that resin infiltration is an effective technique for improving the esthetics of demineralised lesions, with color stability maintained for up to 24 months across included studies, no adverse clinical effects reported, and the timing of application relative to bracket removal shown to influence the quality of the masking outcome.[40]

In a four-year prospective clinical study by Puleio et al., 40 non-cavitated WSLs treated with resin infiltration were assessed by spectrophotometry. The color difference between the lesion and adjacent sound enamel decreased significantly between baseline and immediately post-treatment ($p < 0.05$), and the values remained stable at one- and four-year follow-up examinations, with no statistically significant changes ($p = 0.305$ and $p = 0.337$, respectively).[38] A retrospective two-year evaluation by Brescia et al. in pediatric patients with developmental enamel defects, including molar–incisor hypomineralization, mild fluorosis, and post-traumatic hypomineralization, similarly demonstrated stable esthetic improvement following Icon infiltration.[7] In a case report with four-year follow-up specifically focusing on post-orthodontic WSLs, Cazzolla et al. reported clinically stable esthetic and mechanical outcomes at 6 months, 1 year and 4 years after a single-session Icon infiltration, with no lesion progression and preserved enamel hardness throughout the entire observation period.[41] A prospective one-year clinical study of post-orthodontic WSLs treated with resin infiltration demonstrated stable and significant color improvement at both 7 days and 12 months after treatment, with no statistically significant change in colorimetric values between these two time points, confirming the durability of the masking effect in the orthodontic context.[42]

Despite this favorable long-term profile, several authors have highlighted the susceptibility of infiltrated lesions to extrinsic staining. Resin polymers based on TEGDMA exhibit measurable water sorption and surface roughness changes over time, particularly in patients with frequent consumption of strongly chromogenic beverages such as red wine and coffee.[39,43] An in vitro study simulating 30 days of daily coffee exposure combined with standardised toothbrushing

demonstrated measurable but clinically manageable color changes in Icon-treated specimens, with regular polishing shown to substantially reduce stain uptake by minimising surface microporosities.[43] Similarly, exposure to chromogenic drinks — particularly red tea, black coffee and Arabic coffee — produced progressive and time-dependent discoloration of resin-infiltrated WSLs, with red tea causing the most pronounced ΔE values, underscoring the clinical relevance of dietary counselling for patients treated with RI.[44] Ageing and repeated toothbrushing were shown to influence both color stability and surface roughness of infiltrated lesions, with RI demonstrating superior color stability compared with remineralizing agents such as MI Paste Plus under simulated intraoral conditions.[45] A sequential approach combining fluoride remineralisation prior to resin infiltration improved overall color restorability compared with either modality alone; however, the color stability of this combined approach under staining challenge was found to be inferior to resin infiltration used as a standalone treatment, suggesting a complex interaction between residual mineral structure and chromophore uptake by the TEGDMA matrix.[46] Where extrinsic discoloration occurs, in-office bleaching may help restore brightness comparable to that of sound enamel.[39]

Mechanical and biological properties of infiltrated enamel are also relevant. WSLs exhibit substantially reduced surface microhardness due to mineral loss. The systematic review and meta-analysis by Soveral et al. confirmed that resin infiltration substantially restores enamel microhardness in WSLs and improves surface roughness, with marked improvements when compared with untreated demineralized enamel.[9] An in vitro study comparing Icon resin infiltration with microabrasion and bioactive glass demonstrated that RI produced the greatest reduction in surface roughness and the highest improvement in microhardness among all tested treatments; however, pH cycling adversely affected surface roughness irrespective of the treatment used, underscoring the importance of caries risk control alongside RI.[47] A further in vitro investigation using atomic force microscopy confirmed that resin infiltration applied prior to in-office bleaching significantly improved microhardness and surface roughness of demineralised enamel compared with bleaching alone, with values approaching those of sound enamel after storage in artificial saliva.[48] Comparison of RI with CPP-ACPF and colloidal silica infiltration demonstrated that resin infiltration produced the highest microhardness values among all tested treatments in primary teeth, confirming it as the most effective option for mechanical reinforcement of incipient enamel lesions.[49] Mechanical reinforcement of the porous enamel structure may, in turn, contribute to the long-term stability of the esthetic outcome and to the prevention of further mineral loss. By contrast, fluoride therapy alone, while

effective in promoting fluorapatite formation in the surface zone, generally does not produce comparable mechanical improvement throughout the entire lesion body.

These findings further support the sequential strategy of combining fluoride remineralisation for biological lesion stabilisation, followed by RI for definitive esthetic masking, noting however that whilst the combined approach improves colour restorability, its colour stability under repeated staining challenge may be inferior to RI used as a standalone treatment.[46]

7. Adjunctive and Emerging Approaches

Several additional treatment modalities have been investigated as alternatives or adjuncts to RI and FBT. Self-assembling peptide P11-4 (Curodont) is a biomimetic agent that forms a three-dimensional matrix within the lesion body, promoting de novo hydroxyapatite crystallization. A randomized clinical trial by Alkilzy et al. demonstrated superior caries arrest with SAP P11-4 used together with fluoride varnish compared with fluoride varnish alone in the treatment of non-cavitated occlusal caries lesions.[37] Network meta-analytic data suggest a complementary role for SAP P11-4 alongside RI and FBT in the management of WSLs.[33]

Enamel microabrasion, which combines hydrochloric acid and abrasive particles to remove the outermost defective layer, can be effective in superficial lesions, but it inevitably results in some loss of healthy tooth structure and is therefore considered more invasive than RI.[1,3] Additional adjuncts under investigation include nano-hydroxyapatite-containing pastes and laser-assisted protocols, which may enhance acid resistance or improve resin penetration in selected cases.[1,2]Although promising, these modalities currently play a complementary rather than primary role in clinical practice.

8. White Spot Lesions in the Context of Sport and Physical Activity

Beyond the general orthodontic population, physically active individuals and competitive athletes represent a clinically important subgroup in whom the balance between demineralization and remineralization is frequently disturbed. Systematic and cross-sectional data indicate a high burden of enamel demineralization in this population, with reported dental erosion ranging widely across studies and dental caries affecting a substantial proportion of athletes assessed with the ICDAS index.[50,51] The underlying mechanisms are multifactorial: repeated exposure to acidic and carbohydrate-rich sports, energy and isotonic drinks (typically pH < 5.5), exercise-induced reductions in salivary flow and buffering capacity, dehydration, and mouth breathing during exertion together shift the intraoral environment toward mineral loss.[50,51,52] Swimmers form a particularly high-risk group, partly because of exposure to

improperly buffered pool water, while endurance athletes are subject to prolonged and frequent acid challenge.[52]

These considerations have direct implications for the choice between resin infiltration and fluoride-based therapies in athletes who develop post-orthodontic WSLs. Because the esthetic effect of RI is achieved in a single session and is largely independent of subsequent home-care compliance, it is well suited to athletes with demanding training schedules and high esthetic expectations, whereas FBT and bioactive remineralizing agents remain essential for controlling the ongoing cariogenic and erosive challenge that characterizes this population. Dietary counseling on the timing and frequency of acidic sports drinks, adequate hydration, and reinforcement of fluoride exposure are therefore logical adjuncts to any micro-invasive esthetic treatment in physically active patients, supporting the same sequential, synergistic strategy advocated for the general orthodontic population.[51,52]

9. Clinical Decision-Making and Synergistic Approach

In clinical practice, the choice between RI and FBT should be guided by lesion characteristics, patient expectations, and behavioral factors. Active, recently developed lesions in highly compliant patients may respond well to fluoride-based remineralization combined with optimized oral hygiene and dietary counseling, particularly when esthetic concerns are mild.[1,3,21]

Inactive or persistent post-orthodontic WSLs that fail to respond to several months of remineralization therapy, or that are located in the esthetic zone of patients with high cosmetic expectations, are particularly suitable candidates for resin infiltration.[22,23] Lesion depth and activity, assessed with DIAGNOdent or QLF, should inform the timing of intervention; superficial active lesions may benefit from a sequential approach, in which a period of biological stabilization with fluoride or CPP-ACP precedes resin infiltration.[2,20,33] This synergistic strategy combines the strengths of both modalities: biological lesion arrest and mineral gain through FBT, followed by definitive optical masking with RI.

A simplified comparison of the principal characteristics of the two strategies is provided in Table 2.

Table 2. Comparison of resin infiltration and fluoride-based therapies for post-orthodontic WSL management.

Feature	Resin infiltration (RI)	Fluoride-based therapies (FBT)
Mechanism of action	Mechanical sealing of porous enamel with TEGDMA resin; refractive index matching	Promotion of fluorapatite formation; CPP-ACP delivers Ca/PO_4 ions for surface remineralization
Esthetic outcome	Immediate, clinically significant masking of the lesion	Limited and slow visual improvement; mainly biological
Onset of effect	Single visit, immediately visible	Gradual, over weeks to months
Lesion arrest	Effective via mechanical occlusion of porosities	Effective via dynamic remineralization
Depth of action	Penetration into the lesion body, exceeding alternative materials	Mainly the outer layer of the lesion
Long-term stability	Color stability documented up to 4 years; risk of extrinsic staining	Outcome dependent on continued patient compliance
Invasiveness	Micro-invasive (HCl etching of surface layer)	Non-invasive
Cost and accessibility	Higher per-procedure cost; requires trained operator and proprietary kit	Lower cost; widely available

Patient compliance	Independent of long-term home care for esthetic effect	Highly dependent on consistent home care and recall

10. Limitations and Future Perspectives

Despite the consistent evidence supporting RI, several limitations must be acknowledged. The number of well-designed randomized controlled trials with long-term follow-up exceeding five years remains relatively small, and methodological heterogeneity – including differences in lesion selection, outcome measures (visual scoring, ΔE, ICDAS, DIAGNOdent), and follow-up duration – complicates direct comparisons across studies.[22,33,39] Standardized, validated esthetic outcome metrics and uniform reporting frameworks are needed to facilitate future evidence synthesis.

Long-term color stability data, although encouraging, are still limited beyond the medium-term follow-up reported in most studies, and the susceptibility of TEGDMA-based infiltrants to staining in real-life dietary conditions deserves further investigation. The role of refined application protocols, including repeated etching cycles and adjunctive bleaching, is also of interest.[39]Furthermore, the cost-effectiveness of RI compared to fluoride therapy in different healthcare systems, and the additional benefit of combination strategies such as CPP-ACP or SAP P11-4 followed by RI, warrant systematic evaluation.[37]

Future research should also focus on identifying clinical and biological predictors of lesion response to each modality, refining patient selection criteria, and integrating digital imaging and quantitative outcome assessment to improve diagnosis, monitoring, and treatment of post-orthodontic WSLs.

11. Conclusions

Post-orthodontic white spot lesions remain a frequent and clinically significant complication of fixed appliance therapy, with implications for both dental health and patient satisfaction. Fluoride-based therapies, including topical varnishes, dentifrices, and CPP-ACP-containing pastes, remain the foundation of preventive care and biological lesion arrest, but their capacity to provide rapid and complete optical masking of established lesions is limited.

Resin infiltration with TEGDMA-based systems such as Icon offers a predictable, micro-invasive solution for the immediate esthetic management of post-orthodontic WSLs, with

documented superiority over fluoride therapy in terms of color improvement and durability of effect over several years. Mechanical reinforcement of the porous enamel and obstruction of acid diffusion pathways further support a long-term stabilizing role of RI.

Current evidence supports a synergistic, sequential approach in which fluoride-based therapies and bioactive remineralizing agents are used to stabilize lesions biologically, followed by resin infiltration when esthetic concerns persist. Long-term randomized controlled trials with standardized outcome measures, alongside investigations into emerging adjunctive technologies, will be essential to refine clinical algorithms and optimize the management of post-orthodontic WSLs in everyday orthodontic and restorative practice.

These considerations are of particular relevance to physically active individuals and athletes, in whom dietary acid exposure and exercise-related salivary changes increase susceptibility to enamel demineralization, and in whom the compliance-independent esthetic benefit of resin infiltration, combined with fluoride-based biological stabilization, is especially advantageous.[50,52]

Disclosure

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