Evaluating Direct and Indirect Bonding Techniques - A Comparative Approach to Orthodontic Practice

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Abstract

AIM: This study provides a comparative analysis of direct bonding (DB), indirect bonding (IB), and CAD/CAM techniques, focusing on chairside time, treatment efficacy, bond failure rates, bracket placement accuracy, periodontal parameters, and white spot lesions (WSLs). The objective is to offer evidence-based guidance for clinical practice through a review of recent in vivo and in vitro studies.

METHODS: A manual and electronic search was conducted in PubMed, Google Scholar, and the Cochrane Library between December 2024 and January 2025 using keywords such as "direct bonding," "indirect bonding," "CAD/CAM," and "orthodontics." After applying specific inclusion and exclusion criteria, 21 studies were selected: 16 in vivo, 4 in vitro, and 1 combined. These studies compared bonding techniques regarding time efficiency, accuracy, bond failure, treatment efficacy, periodontal outcomes, and white spot lesions.

RESULTS: The reviewed studies revealed no consistent superiority among bonding techniques concerning bond failure rates or shear bond strength. Indirect bonding generally demonstrated greater accuracy in bracket placement and modest advantages in treatment duration and oral hygiene outcomes, including fewer WSLs. While overall treatment efficiency appeared comparable, IB and CAD/CAM techniques showed potential clinical benefits.

CONCLUSION: All bonding techniques demonstrate comparable overall effectiveness, with no clear advantage in bond strength or failure rates. Indirect bonding and CAD/CAM methods may provide slight clinical benefits in accuracy and oral hygiene, especially in complex cases.

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1 Introduction

Orthodontic treatment has undergone remarkable advancements over the past century, transitioning from banded appliances to the development of more refined and aesthetically pleasing bonded brackets. In recent years, the integration of digital technologies such as computer-aided design and manufacturing (CAD/CAM) and digital bonding techniques has further revolutionised the field, offering greater precision and customisation in the orthodontic domain. Precise and reliable bonding of both brackets and fixed retainers to the enamel surface is fundamental to orthodontic treatment, as it ensures accurate force delivery, promotes long-term retention, and contributes to overall treatment success (Proffit et al., 2019). Currently, there are three primary methods of bonding employed in orthodontic practice: direct bonding (DB), indirect bonding (IB), and CAD/CAM. Each technique offers distinct advantages and limitations, making it essential to understand their differences and clinical applications.

The conventional and most widely used method of bracket placement is DB. Direct bonding involves the placement of braces directly onto the patient's teeth chairside during the treatment session. This method gained popularity in the 1970s due to its simplicity, lower cost, and the elimination of laboratory steps, making it accessible in most clinical settings. On the other hand, direct bonding demands a high level of skill and precision from the orthodontist. Moreover, it has limitations such as poor visual access in posterior regions, potential contamination from saliva or blood, and operator fatigue due to prolonged chairside time (Agarwal et al., 2017; Atilla et al., 2020; Hoekstra-van Hout et al., 2024). These limitations also affect fixed retainer bonding, where passive and precise wire positioning, along with moisture control, are essential for stability, particularly in anatomically challenging regions (Egli et al., 2017; Tran et al., 2024).

These shortcomings have led clinicians to explore IB, which was first introduced by Silverman et al. in 1972 and purported to offer greater precision. Indirect bonding is a two-step process in which the braces are first attached to a model outside the mouth, where visibility and control are optimal, and then transferred to the patient's mouth using a transfer tray that allows for simultaneous placement of multiple brackets (Silverman et al., 1972). This technique has been adopted in both academic and private orthodontic settings due to its reported advantages in bracket positioning accuracy. However, the technique also presents challenges, largely due to the additional costs, time-consuming laboratory phases, and the technique's multi-step sensitivity—where any error during the process can compromise bond strength (Demirovic et al., 2018).

In the early 2000s, the innovation of CAD/CAM technology introduced a new dimension to IB, aiming to enhance precision and customisation. This digital workflow comprises intraoral scanning, virtual bracket positioning using orthodontic software, and 3D-printed transfer trays. CAD/CAM bonding enables patient-specific virtual planning and more accurate bracket placement, thereby facilitating individualised and efficient orthodontic treatment (Czolgosz et al., 2020; Wang et al., 2022). In addition to optimising bracket positioning, CAD/CAM technologies have also been applied to the fabrication and bonding of fixed retainers (Gelin et al., 2020; Shim et al., 2022; Gera et al., 2023; Tran et al., 2024; Pullisaar et al., 2024). Customised retainer wires and trays ensure highly accurate and patient-specific placement. However, CAD/CAM systems have limitations. The technique requires careful coordination with external laboratories, adequate training in digital planning software, and is associated with higher costs compared to other bonding methods (Czolgosz et al., 2021).

A comprehensive evaluation of bonding techniques in orthodontics reveals variability in clinical outcomes such as bond failure rate, shear bond strength (SBS), bracket placement accuracy, periodontal parameters, enamel demineralisation, treatment efficiency, and cost-effectiveness. Despite the growing body of literature comparing direct, indirect, and CAD/CAM bonding techniques, conclusions remain inconsistent due to methodological variability. Differences in sample sizes, study designs, follow-up durations, outcome definitions, and operator experience contribute to the lack of consensus regarding superiority.

This study aims to systematically evaluate and compare direct, indirect, and CAD/CAM orthodontic bonding techniques by analyzing their clinical performance, accuracy, efficiency, cost-effectiveness, mechanical reliability, and hygiene-related outcomes in order to provide evidence-based guidance for optimizing bracket placement and treatment approaches in orthodontic practice.

2 Methods

The studies included in this review were carefully selected based on specific inclusion criteria designed to capture relevant and high-quality evidence comparing direct and indirect bracket bonding techniques in orthodontics. Eligible studies were required to feature both bonding methods within their research design and be published in English within the last decade, from January 2015 to December 2024. Only clinical (in vivo) and laboratory (in vitro) studies were considered to ensure a comprehensive evaluation of treatment efficiency, accuracy, failure rates, treatment time, chair-side time, shear-bond strength, and costs associated with these techniques. Furthermore, only articles with full-text availability were included to facilitate thorough analysis, and the search was guided by precise keywords such as "direct bonding," "indirect bonding," "CAD/CAM," and "orthodontics." The selection process emphasized studies that directly compared at least two bonding approaches to maintain focus and relevance to the research question (**Table 1**).

Table 1. Database search results for direct and indirect bonding and CAD/CAM in orthodontics (English, human studies, last 10 years). Dedup. = after cross-database deduplication; "-" = not applicable / not reported

DATABASE	HITS	FILTER	DEDUP.	INCLUDED
PubMed	2,192	77	-	14
Google Scholar	1,630	491	478	13
Cochrane	166	103	89	2

Conversely, certain studies were excluded to maintain the rigor and specificity of the review. Research concentrating solely on a single bonding technique without comparison, or primarily investigating bonding materials rather than techniques, were omitted. Publications not accessible in English or released before 2015 were excluded to ensure contemporary relevance. Systematic reviews, meta-analyses, and animal studies were also excluded to focus on primary research data from human clinical and laboratory settings. Additionally, studies with unclear methodologies or insufficient detail were omitted to ensure data quality, alongside non-peer-reviewed works such as theses, pamphlets, and other unpublished materials. Further refinement excluded clinical studies with small sample sizes (≤ 20 patients) to avoid statistical limitations, and duplicate studies from the same research groups reporting identical findings over time were consolidated to prevent redundancy. This rigorous filtering process ultimately resulted in a selection of 21 high-quality articles for inclusion in the review. Characteristics of the included in vitro studies are presented in supplementary **Table S1**. Combined in vitro and in vivo studies are presented in **Table 2**.

Table 2. Characteristics of combined in vitro and in vivo studies.

AUTHOR (YEAR)	SAMPLE	DURATION	TECHNIQUES	OUTCOMES
Shaheen (2016)	60 PM	-	DB vs. IB	• Microleakage
Kalra (2018)	13 Models	-	DB vs. IB	• Accuracy
Demirovic (2018)	30 P & 60 PM	6 Mo	DB vs. IB	• Shear-Bond-Strength • Resin remnants • Bond-Failure
Oliveira (2019)	560 Teeth	-	DB vs. IB	• Accuracy
Sohail (2024)	360 Teeth	-	CAD/CAM vs. DB	• Shear-Bond-Strength • Resin remnants • Precision fit

Note: CAD/CAM: Computer-Aided Design/Computer-Aided Manufacturing; DB: Direct Bonding; IB: Indirect Bonding; Mo: Month; P: Patient; PM: Premolar.

2.1 Statistics

Descriptive statistics, frequency analysis, and content analysis were employed as part of the qualitative methodology to systematically analyze the textual content of the included studies. It is important to note that, given the narrative nature of this study, regression analysis and meta-analysis techniques were not deemed suitable for the analytical framework.

3 Results

3.1 Bond failure rate

Among the 14 articles (13 clinical studies and 1 combined study) comparing bond failure rates between direct, indirect, and CAD/CAM bonding methods, only five reported significant differences among the techniques, suggesting that direct bonding shows a lower bracket failure rate (**Table S2**).

One randomised controlled trial (Czolgosz et al., 2021) and one clinical trial (Hegele et al., 2021) found significantly higher bracket bond failure rates in CAD/CAM bonding compared to direct bonding. In the RCT by Czolgosz et al., the bond failure rate was 0% for direct bonding and 5.1% for CAD/CAM bonding ($p = 0.0001$). In the clinical trial, the median [range] bond failures were 1 [0–3] for direct bonding and 2.0 [0–19] for CAD/CAM bonding ($p = 0.035$).

Two randomised controlled trials (Kono et al., 2024; Hoekstra-van Hout et al., 2024) comparing direct and indirect bonding also found significant differences in failure rates, with indirect bonding resulting in a higher incidence of failure. In the study by Kono et al. (2024), the bond failure rate was 7.75% for direct bonding and 20.10% for indirect bonding ($p < 0.001$). In the study by Hoekstra-van Hout et al. (2024), immediate and late failure rates for direct bonding were 0% and 2.5%, respectively, while for indirect bonding they were 3.9% and 5.4%, respectively ($p = 0.008$).

Another randomised controlled trial (Shim et al., 2022), which assessed the three bonding methods for lower jaw retainers, reported that CAD/CAM retainers exhibited fewer failures than laboratory-fabricated (indirect) retainers, but did not demonstrate more favourable failure rates compared to traditional direct retainers. The failure rates were 8% for direct bonding (2/25), 23.3% for indirect bonding (7/30), and 20% for CAD/CAM bonding (4/20), with a statistically significant difference among the groups ($p = 0.045$).

The remaining nine articles found no statistically significant differences in bond failure rates between the above-mentioned bonding methods. This indicates that the overall evidence remains inconclusive regarding which bonding technique offers superior bracket retention (**Table S2**).

3.2 Mechanical and adhesive properties

Two in vitro studies (Demirovic et al., 2018; Sohail et al., 2024) assessed shear bond strength (SBS) and adhesive remnant index (ARI) (**Table S3**). Demirovic et al. (2018) found no significant difference between direct and indirect bonding in terms of SBS and ARI. The other study, by Sohail et al. (2024), found that the CAD/CAM-fabricated retainers exhibited higher SBS values compared to two directly bonded retainers (braided stainless steel and co-axial types), with a mean SBS of 189 ± 55.10 N ($p < 0.001$). The CAD/CAM retainers also had the highest mean ARI score (33.90), although the difference was not statistically significant ($p = 0.509$). Furthermore, in this article, CAD/CAM-bonded retainers had a significantly more precise fit compared to conventional retainers (0.038 ± 0.022 mm vs. 0.204 ± 0.065 mm, $p = 0.009$).

As only two studies assessed shear bond strength and reported conflicting results, no definitive conclusion can be drawn regarding which bonding method provides superior mechanical performance. Only one in vitro study (Shaheen et al., 2016) evaluated microleakage between direct and indirect bonding techniques and reported no statistically significant difference between the two methods (direct: 0.0988 mm; indirect: 0.0916 mm; $p > 0.05$).

3.3 Accuracy

Several in vitro and clinical studies have evaluated the accuracy of direct bonding (DB) versus indirect bonding (IB) techniques in bracket placement (Table 6). Results from these studies indicate that indirect bonding generally offers greater accuracy than direct bonding.

One in vitro study by Kalra et al. (2018), conducted on 13 models, revealed no overall statistically significant difference between the two techniques. However, IB showed superior accuracy in specific instances, such as bracket height on tooth 34, horizontal positioning on teeth 13 and 34, and angulation on teeth 14 and 44 ($p \leq 0.05$) (**Table S4**).

Furthermore, a more extensive in vitro study involving 560 teeth by Oliveira et al. (2019) found that IB was significantly more accurate than DB across all dimensions. The mean deviation from the ideal position was 2.89° for IB versus 3.18° for DB in angulation ($p = 0.004$), 0.24 mm versus 0.33 mm in mesio-distal positioning ($p = 0.004$), and 0.49 mm versus 0.58 mm in vertical accuracy ($p < 0.001$). The overall placement correctness was 64.6% for IB compared to 27.1% for DB.

These findings are further supported by clinical studies (Agarwal et al., 2017; Hoekstra-van Hout et al., 2024). In particular, the study by Hoekstra-van Hout et al. (2024), involving 35 patients, reported significantly better results for IB in both angulation (IB: 3.40° vs. DB:

8.24°, $p < 0.001$) and translation deviation (0.38 mm vs. 0.73 mm, $p = 0.017$).

3.4 Chair time, overall time, and treatment time

All three articles comparing chair time and overall time (including both chair-side and laboratory procedures) consistently found that IB and CAD/CAM techniques significantly reduced chair time compared to DB (**Table S5**).

For instance, Yildirim et al. (2018) reported a substantial reduction in chair time for IB (26.51 ± 3.33 minutes) compared to DB (53.02 ± 4.72 minutes), with a highly significant difference ($p < 0.001$). In this study, however, the overall time was longer for IB (72.05 ± 5.2 minutes), suggesting that DB may outperform IB when laboratory work is included. Another study by Kono et al. (2024), involving 124 participants, further confirmed this pattern, with IB showing a markedly shorter mean chair time (35.91 ± 15.51 minutes) compared to DB (58.52 ± 25.24 minutes, $p < 0.001$).

Regarding treatment duration, the results were mixed. The randomised controlled trial (RCT) by Yildirim et al., involving 30 patients, found no significant difference between techniques. In contrast, a larger RCT by Kono et al. demonstrated that indirect bonding significantly reduced treatment duration compared to direct bonding (Direct: 34.27 ± 8.87 months vs. Indirect: 30.51 ± 7.27 months, $p < 0.01$). Among two controlled trials assessing treatment time, Wang et al. (2022) reported a significantly shorter overall treatment duration for CAD/CAM compared to direct bonding ($p = 0.04$), with CAD/CAM reducing treatment by approximately four months (DB: 21:20 ± 7:14; CAD/CAM: 17:17 ± 4:16). The other controlled trial by Hegele et al. (2021), involving 38 patients, found no significant difference between the direct and CAD/CAM techniques ($p = 0.654$).

Overall, treatment time results across studies were inconsistent and neither bonding method demonstrated clear and consistent superiority. However, the overall trend appears to favour indirect bonding with respect to treatment duration.

3.5 Plaque and white spot lesions

Among the four RCT studies that examined plaque accumulation and white spot lesions (WSLs) across different orthodontic bonding techniques, only one article (Atilla et al., 2020) with 51 patients reported statistically significant differences between DB and IB. Using quantitative light-induced fluorescence (QLF) to measure demineralisation at the beginning and end of treatment for each tooth, it was observed that the DB group developed more WSLs overall ($p < 0.05$). Although a few teeth in the IB group, particularly the mandibular left canine (50.45 ± 93.48; 95% confidence interval: -12.35 and 113.26, $p < 0.05$), showed significant WSL formation, the total number of affected teeth was higher in the DB group (**Table S6**).

Other studies (Yildirim et al., 2018; Gelin et al., 2020; Kono et al., 2024) showed no statistically significant differences between the techniques regarding plaque index or WSLs.

Overall, the available evidence does not support a clinically relevant difference in plaque accumulation or white spot lesion development between direct and indirect bonding techniques. Therefore, the choice of bonding method appears not to influence these oral health outcomes.

3.6 Effectiveness and post-treatment changes

Several studies assessed effectiveness and post-treatment stability of DB, IB, and CAD/CAM techniques using multiple orthodontic parameters (**Table S7**).

The American Board of Orthodontics' Objective Grading System (ABO/OGS) was frequently used to evaluate treatment outcomes. One RCT (Yildirim et al., 2018) found IB to be significantly more effective than DB, reporting better total OGS scores ($\Delta = -3.999$; 95% CI: -6.000 to -0.005; $p = 0.03$) and improved marginal ridge alignment ($p = 0.03$). Similarly, another RCT (Kono et al., 2024) reported lower ABO Occlusal Index (Cast-Radiograph Evaluation, CR-EVAL) scores in the IB group compared to DB (47.31 ± 8.17 vs. 53.24 ± 7.74; $p < 0.001$), indicating superior occlusal finishing in the indirect group. Furthermore, the study by Hegele et al. (2021) reported that CAD/CAM offered better control over lower incisor protrusion ($p < 0.05$), although it required more frequent wire changes ($p < 0.001$). By contrast, Wang et al. (2022) found no significant differences between the DB and CAD/CAM groups regarding cephalometric ABO scores ($p > 0.05$).

In terms of post-treatment stability, Tran et al. (2024) reported significantly less reduction in inter-canine width in the CAD/CAM group compared to chairside DB ($p < 0.05$) at all time points and compared to IB at 6 months ($p = 0.038$). Additionally, LII scores increased significantly less in CAD/CAM patients compared to both DB and IB groups ($p < 0.05$), indicating better anterior alignment stability. These findings were reinforced by the study of Shim et al. (2022), which showed greater preservation of inter-canine width compared to DB at all follow-up points, and lower LII values ($p < 0.05$) compared to IB at the 3-month follow-up.

Several studies (Egli et al., 2017; Gelin et al., 2020; Cornelis et al., 2022; Gera et al., 2023) did not report significant differences between groups regarding inter-canine width (ICW), inter-premolar distance (IPD), or arch dimensions; however, some notable trends were observed. For example, in a 5-year follow-up, one study (Cornelis et al., 2022) identified more cases of torque changes in the front teeth in the DB group (6 out of 26 patients), despite no significant changes in ICW or IPD between groups.

Overall, studies consistently showed that CAD/CAM bonding maintained superior control over tooth positioning and arch form during the post-treatment period, especially regarding ICW, LII, and incisor inclination, even if not all differences reached statistical significance.

3.7 Costs

Only two articles discussed the costs and expenses of different methods, presenting completely opposite results. One randomised controlled trial (RCT) article (Czolgosz et al., 2021) with 27 patients concluded that CAD/CAM costs were slightly higher for the computer-aided indirect bonding method than for the direct bonding method (**Table S8**). For direct bonding, the total cost is €112, which includes orthodontist time, dental assistant time, and chair time. For indirect bonding, two scenarios are shown. In Scenario A (2 min of the orthodontist's time for checking the digital bracket placement), the total cost is €128, and in Scenario B (5 minutes of the orthodontist's time for checking the digital bracket placement), it is €132. These costs include various components such as dental assistant time, lab technician digital bracket placement, indirect bonding tray, and orthodontist time for checking digital placement.

In contrast, a cost-minimization analysis conducted alongside another RCT (Pulisaar et al., 2024) showed that conventional fixed retainers (FRs) were approximately 10% more expensive compared to CAD/CAM FRs over a 24-month period. The initial bonding cost is €111 for CAD/CAM and €126 for the conventional method. Expected costs for repairs due to debonding, wire fracture, and combined debonding and wire fracture were also considered. The total cost per patient amounts to €290 for CAD/CAM and €327 for conventional FR bonding.

4 Discussion

Based on 29 included articles this review compared direct bonding, indirect bonding, and CAD/CAM methods, focusing on chairside time, treatment effectiveness, bond failure rates, bracket placement accuracy, periodontal outcomes, and white spot lesions.

4.1 Accuracy and treatment efficiency

Concerning bracket placement accuracy, the literature generally supports that indirect bonding, particularly when enhanced by digital planning and customised tray fabrication, offers more precise bracket positioning than direct bonding. However, this advantage is highly context-dependent.

Kalra et al. (2018), who utilised conventional, non-digitally fabricated trays under idealised laboratory conditions, reported no significant accuracy advantage for IB. The use of a semi-digital IB protocol, combined with multiple operators and the absence of clinical challenges such as moisture and limited visibility, may have masked subtle technique-related differences. Conversely, Agarwal et al. (2017), who conducted the study in a clinical setting, observed consistent accuracy benefits with IB despite using a similar tray design.

These findings suggest that the accuracy benefits of IB are most evident when supported by digital planning and customised tray fabrication; even when clinician input is included; and are less pronounced in semi-digital approaches under idealised laboratory conditions.

Nevertheless, greater accuracy does not always equate to improved treatment efficiency. When evaluating effectiveness in terms of treatment outcomes, findings remain mixed and appear to be influenced more by contextual variables than by the bonding method itself. Kana Kono et al. (2024) reported significantly improved occlusal outcomes with IB, using the CR-Eval index, a component of the ABO grading system considered more sensitive to fine occlusal discrepancies than other individual ABO scoring parameters. Additionally, the relatively limited experience of the postgraduate operators may have exaggerated the precision advantage of IB. In contrast, both Wang et al. (2022) and Hegele et al. (2021), employing experienced practitioners and conventional outcome measures such as ABO scores and cephalometric analysis, found no significant differences between IB and DB, suggesting that with protocol consistency and operator expertise, both techniques can achieve comparable results.

Post-treatment retention outcomes illustrate this pattern of variability. Shim et al. (2022) observed better short-term stability with CAD/CAM retainers made from rigid Denta-flex wires, likely due to their resistance to deformation. However, Gera et al. (2023), using more flexible nitinol wires and a dual retention protocol (fixed plus removable retainers), found no significant difference between CAD/CAM and conventional retainers after six months. These discrepancies may be due to differences in wire material properties and adjunctive retention methods. Additionally, both studies relied on Little's Irregularity Index (LII), which lacks sensitivity for capturing three-dimensional changes, such as vertical discrepancies and rotational misalignments. Consequently, it lacks sensitivity in detecting subtle but clinically relevant changes in tooth positioning.

Longer-term studies by Gelin et al. (2020) and Pullisaar et al. (2024), with follow-ups of 12 and 24 months, respectively, found no meaningful differences between CAD/CAM and conventional retainers, suggesting that the initial precision of CAD/CAM systems may not lead to lasting clinical advantages.

Overall, these findings indicate that neither indirect bonding nor CAD/CAM-based techniques consistently outperform traditional methods across all clinical settings. While they may improve precision and short-term outcomes under specific conditions, their advantages are highly dependent on factors such as case complexity, operator experience, clinical environment, and the type of appliance used. In particular, the accuracy advantage of IB appears to be context-dependent, becoming more pronounced when digital workflows are implemented and procedures are carried out under realistic clinical conditions.

4.2 Chairside time, treatment duration, and cost-effectiveness

Understanding the differences of bonding techniques in view of chair-side time, overall treatment duration, and cost-effectiveness, helps determine which method offers the most efficient and practical advantage in various treatment settings.

Indirect bonding, particularly when supported by digital workflows, has been associated with reduced treatment time in some studies, such as those by Kana Kono et al. (2024) and Wang et al. (2022). Both studies involved broader malocclusion types and highlighted the advantages of precise bracket placement in reducing the need for mid-treatment adjustments. In contrast, studies focusing on simpler cases (e.g., Class I malocclusion), such as those by Yıldırım et al. (2018) and Hegele et al. (2021), found no significant differences in overall treatment duration between IB and DB. This suggests that in straightforward clinical scenarios, where bracket repositioning is less frequent and treatment plans are more predictable, the potential time savings of IB are less likely to manifest.

The appliance system itself is also a key factor. For example, a comparison between CAD/CAM-based indirect bonding (IB) and self-ligating direct bonding (DB) shows that the inherent efficiency differences between bracket systems can mask the effect of the bonding method alone (Hegele et al., 2021). Additionally, factors such as the use of standardised appointment intervals or the same experienced operator across all treatments, as seen in both Yıldırım et al. and Hegele et al., may neutralise technique-dependent variation, further narrowing the efficiency gap between IB and DB.

These findings suggest that the benefits of indirect bonding on treatment duration become more apparent in complex cases or when used alongside digital technologies that enhance placement accuracy. In contrast, for simple malocclusions or when using high-efficiency appliance systems like Damon brackets, the choice of bonding technique may have a negligible effect on treatment length. Additionally, factors such as operator consistency (i.e., using the same orthodontist for all cases) and the experience level of the clinician play an important role. More experienced practitioners may compensate for less accurate initial bracket placement through efficient in-treatment adjustments, thereby minimising any time advantage of indirect bonding. Moreover, study protocol design (e.g., appointment intervals) and sample characteristics (e.g., malocclusion class, growth status, and patient compliance) also significantly influence outcomes and must be considered when interpreting treatment time across studies.

While total treatment time remains inconclusive across studies, the findings are more uniform when assessing chair time. All studies evaluating both chairside and total procedure time consistently reported that IB significantly reduces chair time due to the extraoral placement of brackets. However, this benefit is offset by increased laboratory or digital preparation demands, making IB more time-consuming overall from the clinician's perspective.

Cost considerations in bonding technique selection depend not only on material and procedure but also on regional economic contexts. Czolgosz et al. (2021) found CAD/CAM bonding more expensive than direct methods, primarily due to additional costs for digital planning, laboratory steps, and 3D-printed trays. Pullisaar et al. (2024), however, reported CAD/CAM retainers as slightly more affordable than conventional retainers over a 24-month period, but noted this was context-dependent; highlighting how differences in auxiliary staff wages and lab fees between countries can alter cost-efficiency. Although Gelin et al. (2020) did not perform a formal cost comparison, their observation that the CAD/CAM retainer was nearly three times more expensive than conventional multistranded wires reinforces the financial variability of these systems. Ultimately, while CAD/CAM and IB techniques may enhance efficiency, their cost-effectiveness is closely tied to local infrastructure, labour costs, and resource availability.

4.3 Plaque and white spot sesions

The development of white spot lesions (WSLs) and plaque accumulation are well-recognised complications of fixed orthodontic treatment, primarily due to the mechanical difficulty of maintaining oral hygiene around brackets. This section explores whether different bonding techniques influence these outcomes and highlights any notable differences identified across studies. Among the reviewed studies, only Atilla et al. (2020) provided evidence supporting the advantage of the indirect bonding technique in reducing WSL development. This study suggests that indirect bonding may reduce the incidence of WSLs, potentially due to the use of low-viscosity materials like flowable composite, which may seal the enamel surface more effectively and reduce plaque retention. Their use of quantitative light-induced fluorescence (QLF) further supports the reliability of their findings.

However, other studies, including those by Yıldırım et al. (2018) and Kono et al. (2024), did not observe significant differences in plaque indices or WSL formation between IB and DB. The absence of significant differences in periodontal parameters across studies likely stems from several confounding factors. First, conventional indices such as the Plaque Control Record (PCR) and Gingival Index (GI) may lack the sensitivity to detect subtle variations in oral hygiene status. Additionally, high patient compliance, socio-economic status, and consistent use of preventive measures like fluoride may have overshadowed any minor effects attributable to bonding technique.

Discrepancies between studies may also be explained by differences in sample characteristics, detection methods (e.g. QLF vs. visual inspection), operator skill, and the type of materials used. Moreover, in cases involving severe crowding, challenges in bracket placement and limited access for oral hygiene, particularly during the alignment and levelling phase, can lead to increased plaque accumulation and WSL development. Although indirect bonding may offer more accurate bracket placement, creating smoother and less plaque-retentive surfaces, its potential benefits appear secondary to patient-specific factors and adherence to preventive protocols. With respect to overall periodontal health, none of the reviewed studies identified substantial differences attributable to the bonding method. However, in combination with effective oral hygiene practices, IB may support improved long-term outcomes.

4.4 Bond strength and bracket failure

To address the question of which bonding technique provides greater mechanical reliability, such as shear bond strength (SBS), bracket failure rates, adhesive remnant index (ARI), and microleakage, the reviewed studies examined these parameters to draw meaningful comparisons. Evidence suggests that IB and CAD/CAM systems may be more susceptible to early debonding when the curing light is compromised by tray design or occlusal interference, particularly in the mandibular region. For instance, both Kana et al. (2024) and Hoekstra van Hout et al. (2024) reported significantly higher failure rates with IB, attributing them to limited light transmission through the transfer trays and reduced pressure application via the intervening base resin. Similarly, Czolgosz et al. (2021) noted that CAD/CAM jigs, although transparent, could partially block light exposure, leading to compromised polymerisation.

When examining retainer systems, Shim et al. (2022) reported more failures in CAD/CAM retainers using Denta-flex wires, which, despite their rigidity, were more prone to deformation. Traditional retainers using flexible Ortho-Flex-Tech wires showed better adaptability under stress. Tran et al. (2024) confirmed no significant difference over two years but noted the dual effect of Ortho-Flex-Tech wires: while their flexibility allows physiological tooth movement, it may also lead to fatigue failure over time.

However, longitudinal studies such as those by Gera et al. (2023), Pullisaar et al. (2024), Gelin et al. (2020) and Cornelis et al. (2022) (5-year follow-up) suggest that bracket or retainer failure rates between IB and DB, or CAD/CAM and conventional systems, tend to converge over time. This time-dependent convergence implies that while early failures may occur more frequently in digitally assisted systems, long-term differences are less pronounced if protocols are followed consistently.

Operator experience is another crucial factor. Although clinical inexperience has been linked to higher early failure rates, Czolgosz et al. (2021) demonstrated that IB has a relatively short learning curve, with performance levelling after four cases and showing no major difference between novice and experienced operators.

Limitations specific to IB may also contribute to bracket loss. Unlike DB, IB does not allow real-time bracket adjustment during levelling, especially in posterior regions exposed to high occlusal loads. This inability to adapt bracket positioning post-placement may increase the risk of debonding under functional stress (Ayyed et al., 2020; Kono et al., 2024). Tran et al. (2024) further identified variability in CAD/CAM fabrication: manual versus machine-bent retainers and scanner type were key factors influencing bond performance, underscoring the need for standardisation in digital workflows.

Considering mechanical performance outcomes, such as SBS, ARI, and microleakage. Demirovic et al. (2018) and Shaheen et al. (2016) found no significant differences between direct and indirect bonding. In contrast, Sohail et al. (2024) reported superior outcomes with CAD/CAM retainers due to their precise intraoral fit and more uniform adhesive layer. These advantages likely reflect the influence of advanced digital customisation rather than bonding method alone.

While direct bonding generally exhibits lower early failure rates under typical clinical conditions, indirect bonding and CAD/CAM techniques may achieve comparable long-term outcomes if implemented with proper protocols, adequate curing, and operator training. Mechanical reliability is not solely dictated by the bonding method but arises from a combination of tray design, appliance type, adhesive system, and clinical handling.

Conclusions

Across the reviewed studies, IB consistently demonstrated reduced chair-side time. However, this benefit was often offset by longer laboratory or digital preparation, making the overall time advantage less significant. Treatment duration may be shortened in complex malocclusions when IB or CAD/CAM techniques are used. Yet, in simpler cases, DB, when applied by experienced clinicians under standardised protocols, can yield similarly efficient results. Hygiene-related outcomes were largely comparable between techniques, with patient compliance, oral hygiene habits, and preventive care having a greater influence than the bonding method. IB, particularly with digital planning, showed improved placement accuracy, though DB achieved similar results in controlled clinical conditions. Post-treatment stability and overall treatment outcomes did not significantly differ across techniques, with long-term effectiveness being consistent when procedures were properly executed. Bond strength and bracket failure rates showed more variability. IB and CAD/CAM methods were sometimes linked to higher early failure rates, though these differences tended to diminish in longer-term follow-up.

The choice of bonding method should be guided by clinical complexity, operator skill, patient compliance, and available technology rather than technological novelty alone. Future research should prioritise long-term, multicentre studies using standardised outcome measures and cost-benefit analyses. This will help clinicians make informed decisions about the most appropriate bonding technique based on evidence, rather than trend, and ensure optimal care tailored to each patient's needs. As digital dentistry continues to evolve, overcoming the current limitations of IB and reducing associated costs will be essential for wider adoption.

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Ethical approval

No ethical approval was required for this study as it did not involve human participants, animal subjects, or sensitive data. This study falls under the category of data collection without participant identification.

Consent for publication

Not applicable.

Authors' contributions

The author(s) declare that all the criteria for authorship designated by the International Committee of Medical Journal Editors have been met. More specifically, these are: (a)

Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND (b) Drafting the work or revising it critically for important intellectual content; AND (c) Final approval of the version to be published; AND (d) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Competing interests

The author(s) declare that there are no competing interests related to this work.

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