Original Article

Evaluation of the accuracy of digital indirect bonding vs. conventional systems: a randomized clinical trial

Eloisa Peixoto Soares Ueno[a]; Teresa Cristina Alvez da Silva Gonzalez de Carvalho[b]; Lylian Kazumi Kanashiro[c]; Weber Ursi[d]; Israel Chilvarquer[e]; José Rino Neto[e]; João Batista de Paiva[f]

ABSTRACT

Objectives: To compare the accuracy and chair time of self-ligating brackets using direct bonding, traditional indirect bonding (IB), and computer-aided design/computer-aided manufacturing (CAD/CAM) IB techniques after orthodontic leveling and alignment.

Materials and Methods: Forty-five patients were randomly assigned to three bonding groups (G1 [n = 15], G2 [n = 15], and G3 [n = 15]). Evaluation after the alignment and leveling phases used two parameters of the objective grading system of the American Board of Orthodontics for root parallelism and posterior marginal ridges, assessed using panoramic radiographies (PR I and PR II), a digital model, and a plaster model. Blinding was only applied for outcome assessment. No serious harm was observed except for gingivitis associated with plaque accumulation.

Results: Although G3 showed better numerical results, they were not statistically significant in the radiographic or model evaluations ($P > .001$). Mean chair time was significantly shorter in G3 (1.1 ± 11.8 min) vs. G1 (56.7 ± 7.3 min) and G2 (52.8 ± 8.3 min; $P < .001$).

Conclusions: The CAD/CAM IB system for self-ligating brackets was as effective as conventional methods, with a shorter chair time. (*Angle Orthod*. 2025;95:3–11.)

KEY WORDS: Digital bonding; Digital flow; Indirect bonding; CAD/CAM; Digital trays

INTRODUCTION

Recently, digital technology has revolutionized orthodontic procedures by enhancing bonding accuracy, reducing chair time, and shortening treatment duration.[1–3]

[a] Researcher, Department of Orthodontics, School of Dentistry, University of São Paulo, São Paulo, Brazil

[b] Reader, Department of Radiology, School of Dentistry, University of São Paulo, São Paulo, Brazil

[c] Full Professor, Department of Orthodontics, School of Dentistry, University of São Paulo, São Paulo, Brazil

[d] Full Professor, Department of Orthodontics, School of Dentistry, State of São Paulo University, São José dos Campos, Brazil

[e] Full Professor, Department of Orthodontics, School of Dentistry, University of São Paulo, São Paulo, Brazil

[f] Professor and Department Chair, Department of Orthodontics, School of Dentistry, University of São Paulo, São Paulo, Brazil

Corresponding author: Eloisa Peixoto Soares Ueno, DDS, MD, Orthodontic Department, School of Dentistry, University of São Paulo, Av. Prof. Lineu Prestes, 2227, São Paulo, São Paulo 05508-000, Brazil
(e-mail: elosoares@cos.odo.br)

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Achieving balanced occlusion after orthodontic treatment depends on the precise diagnosis, planning, bracket positioning, and biomechanics. Proper bracket bonding is crucial for esthetic results and optimal occlusal force distribution during chewing. Essential aspects include tooth alignment, root parallelism, and leveling of the marginal ridges for functional balance and stability.[4–7]

Direct bonding (DB), considered the traditional approach, necessitates skill and understanding of dental anatomy. Nevertheless, challenges may arise owing to inherent anatomical variations, malocclusion, and potential human error, particularly during the leveling phase or upon the initial insertion of rectangular wires. These instances may reveal potential inaccuracies in bracket positioning.[4–8]

In 1972, Silverman et al.,[9] introduced indirect bonding (IB) to enhance bracket positioning accuracy and minimize errors by improving spatial vision. This technique requires additional laboratory time for positioning brackets on plaster models (PMs) and using individualized trays for transfer and bonding.[9–17] Various transfer trays have been studied, including hot glue, polyvinyl siloxane putty (PVS-putty), double polyvinyl siloxane, and thermoplastic trays.[11,18,19] Despite the good bond

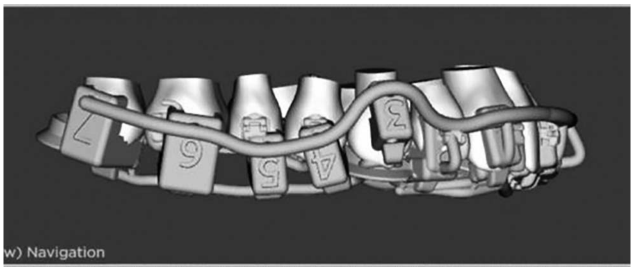

Figure 1. Computer-aided design/computer-aided manufacturing (CAD/CAM) digital tray for indirect bonding (IB).

strength of IB techniques, several investigators have reported accuracy inconsistencies.[20–25] Koo et al.[26] noted improved bracket height positioning in IB but no statistically significant differences in mesiodistal positioning and bracket angulation. Yildirim and Saglam-Aydinatay,[27] in a clinical trial comparing conventional direct and indirect techniques for successful positioning, reported minor inconsistencies in marginal ridge leveling with IB. Reports in the literature also suggested an inconsistency regarding the positioning side of brackets, where the left side (LS) was found to be more effective, regardless of the bonding type.[23]

Technological advancements, such as computer-aided design/computer-aided manufacturing (CAD/CAM) software, have emerged to aid in planning, bracket positioning, and transfer accessory construction.[1,2,12,15,28–32] Authors of some studies have compared CAD/CAM systems with customized appliances. Still, none have compared CAD/CAM technology in planning the positioning of prefabricated brackets and manufacturing transfer trays using indirect and direct techniques.[33–37]

In this study, we compare digital flow and conventional bonding techniques to achieve successful leveling and improve the final tooth positioning in bone bases.

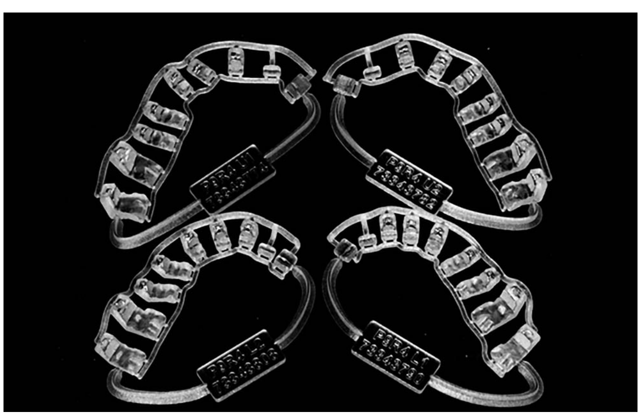

Figure 2. Computer-aided design/computer-aided manufacturing (CAD/CAM) transfer trays for indirect bonding (IB).

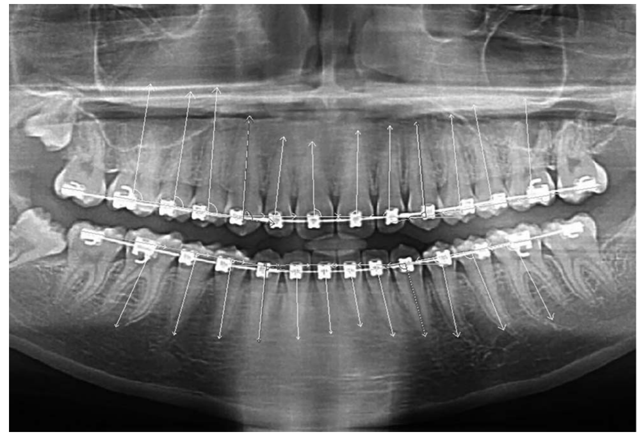

Figure 3. Panoramic radiography I (PR I).

MATERIALS AND METHODS

Trial Design and Any Changes After Trial Commencement

This was a three-arm parallel-group, randomized, active-controlled trial with a 1:1 allocation ratio.

Registration

Permission to conduct this study was approved by Ethics and Research Committee of the Faculty of Dentistry of the University of São Paulo: CAAE:857830 18.9.0000.0075; Protocol: 2.585.017; Brazilian Registry of Clinical Trials platform: RBR-6zpvwty.

Participants, Eligibility Criteria, and Settings

The eligibility criteria included a balanced facial profile, Class I or half-cusp Class II occlusion, complete permanent dentition excluding third molars, ability to bond all brackets during the initial consultation, no prosthetic rehabilitations or extensive restorations, no carious lesions, white spots, or dental abnormalities,

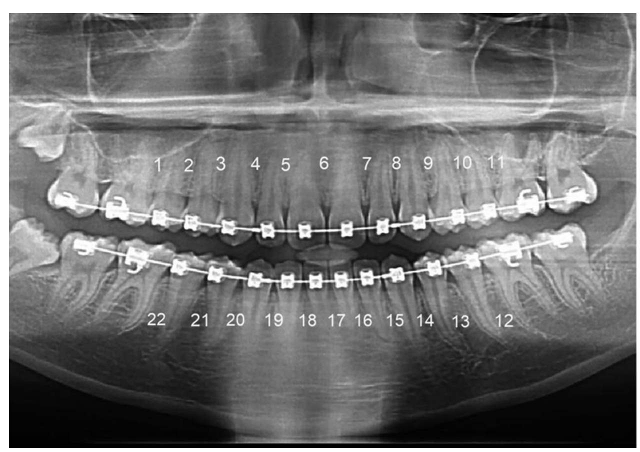

Figure 4. Panoramic radiography II (PR II).

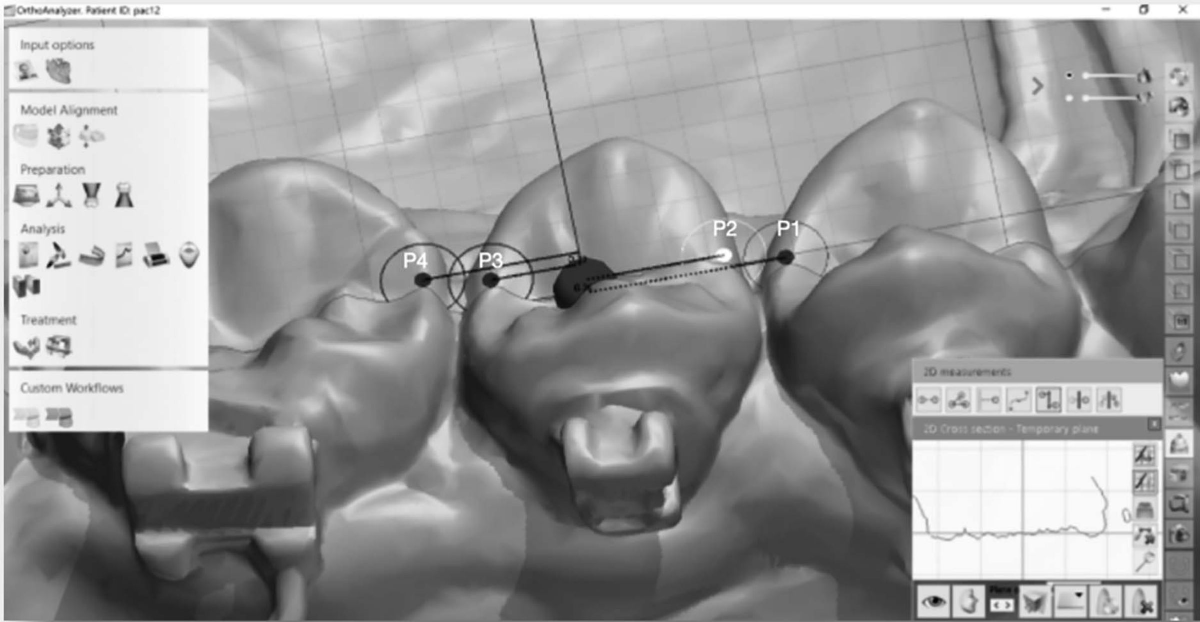

Figure 5. Digital model (DM).

good hygiene (no gingivitis or periodontal diseases), no systemic diseases, no severe crowding or bimaxillary protrusion, or indications for tooth extraction.

Sample Size Calculation

The sample size was determined based on previous studies[34,35] and the requirement of a sample *t*-test (25 individuals). A parametric analysis of variance (ANOVA) was employed, with a minimum of 12 patients per group. Three additional patients were included in each group to account for potential losses, resulting in 15 patients per group. The calculation considered an α error of 5% and a power of 80% using G-Power version 3.1.9.2 (Franz Faul, University of Kiel, Kiel, Germany). A total of 450 patients was assessed, and 45 met the criteria.

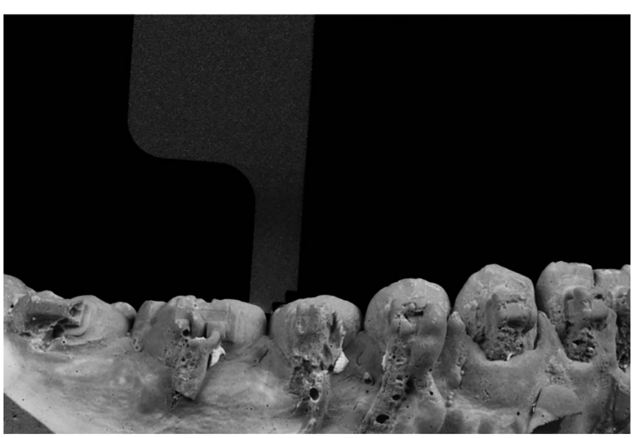

Figure 6. Plaster model (PM).

Randomization

Randomization was performed with the number of sequences generated using a random function in Excel with a 1:1 allocation ratio (Excel 15.0, 2023, Microsoft Corporation, Redmond, Wash). The list of participants was randomly arranged and divided into three groups: G1 (DB), G2 (ID), and G3 (CAD/CAM). To prevent selection bias before the randomization procedure, a different investigator converted the participants' names into numbers to ensure allocation concealment.

Interventions

Self-ligating brackets (Damon Q; Ormco, Orange, Calif) were used in all three groups: G1, DB with Transbond XP adhesive composite (3M Dental Products, St Paul, Minn); G2, IB on PMs using Transbond XP and trays made with PVS-putty (Zeta Plus Soft Zhermack SPA, Rome, Italy) and Custom I.Q. IB Sealant (Reliance Orthodontics Products, Itasca, Ill); G3, digital bracket positioning on a digital setup with complete digital flow using CAD/CAM-printed trays (Suresmile-Elemetrix, Dentsply-Sirona, Charlotte, NC; Figures 1 and 2) bonded with Transbond XP.

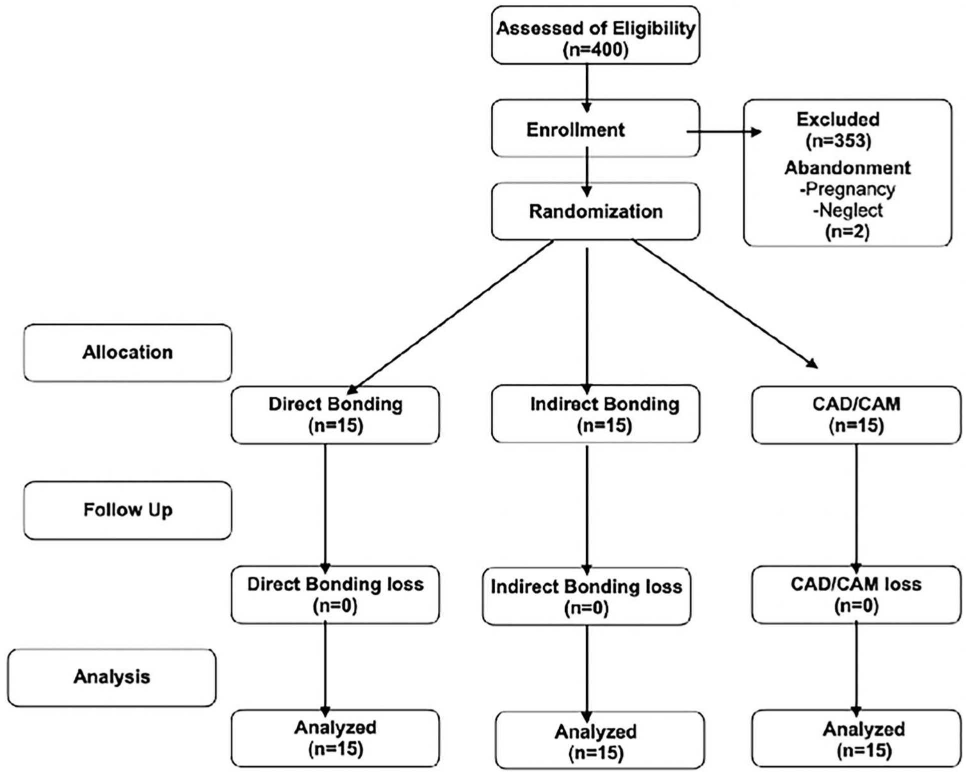

Figure 7. CONSORT flow chart.

Polymerization during clinical procedures involved two operators: one for tray compression and the other for conducting the polymerization. The breaks in the DB were made directly on the teeth. The ID was constructed in individual trays, and a detachable tray cocoon facilitated CAD/CAM technology with rebonding. A single ID operator with 20 years of experience in ID (EPSU, the first author) performs all clinical, laboratory, and digital procedures. A digital chronometer recorded the chair time from initial acid etching of the tooth enamel through completion of bracket polymerization. Copper Ni-Ti archwires 0.014", 0.018", 0.014" $\times$ 0.025", and 0.018" $\times$ 0.025" (Damon Q; Ormco, Orange, Calif) were used for leveling and alignment. Measurements were conducted 4 weeks after final archwire placement.

Outcomes

Measurements were performed using panoramic radiographs (PRs), digital models (DMs), and PMs. Two parameters of the American Board of Orthodontics (ABO)—root parallelism and vertical differences between the posterior marginal ridges—were used to analyze accuracy (Figures 3 through 6).

Table 1. Sample Demographics[a]

	n	Median Age (y)	Males (n)	Females (n)
G1	15	16.8	8	7
G2	15	16.1	10	5
G3	15	16.5	7	8

[a] (*P*) Kruskal-Wallis = 0.3669. Show no significant differences between groups.

Blinding

Blinding of either patient or operator was not possible. All data were assigned a random code numbered by a research assistant to blind the evaluator during the measurements and data analysis.

Error in the Method

Ten randomly selected individuals were assessed for intraexaminer and interexaminer reliability. For all outcomes, the intraclass correlation coefficient (ICC) values were $>$0.9 for intrarater and $>$0.8 for interrater, demonstrating reliability and consistency of the evaluation techniques.

Statistical Analysis

SPSS for Windows (version 22.0; IBM Corp., Armonk, NY) was used. The significance level was set at 5%. ICCs were used for the PR numerical evaluation. The standard deviations and summary measures were calculated. The bonding techniques of the PR and DM methods were compared. ANOVA followed by Bonferroni comparisons were used for chair times. Two-factor ANOVA was used for side comparisons. The ABO

Table 2. Variability Panoramic Radiography (PR) I and II, Digital Models (DMs), Plaster Models (PMs), and Bonding Time Between Bonding Techniques[a]

	Bonding Type			
Variable	Direct (N = 15)	Indirect (N = 15)	Digital (N = 15)	P
SD PR I				.247
Mean ± SD	7.02 ± 1.66	7.77 ± 1.42	7.04 ± 0.99	
Median (min, max)	6.6 (4.7, 9.9)	8.1 (5.4, 10.2)	6.9 (5.6, 8.9)	
SD PR II				.652[b]
Mean ± SD	2.33 ± 1.4	2.8 ± 2.04	2.07 ± 1.49	
Median (min, max)	2 (0, 4)	2 (0, 7)	2 (0, 5)	
DM				.117
Mean ± SD	3.93 ± 1.33	4.14 ± 1.29	3.25 ± 0.95	
Median (min, max)	3.4 (2.6, 6.7)	4.1 (2.3, 6.5)	3.3 (2.1, 5.7)	
PM				.989[b]
Mean ± SD	1.67 ± 1.8	1.4 ± 0.99	1.4 ± 0.99	
Median (min, max)	1 (0, 5)	1 (0, 3)	1 (0, 3)	
Chair time (min)				<.001[c]
Mean ± SD	56.7 ± 7.3	52.8 ± 8.3	41.1 ± 11.8	
Median (min, max)	56 (39, 68)	54 (42, 75)	38 (25, 65)	

[a] Analysis of variance.
[b] Kruskal-Wallis test.
[c] Show no significant differences between the groups PR I, PR II, DM, and PM. Statistically significant differences were found in bonding time.

indices were compared using the Kruskal-Wallis test. Differences with $P < .05$ were considered significant.

RESULTS

Participant Flow

Recruitment began in March 2018 and ended in November 2018. Initially, 400 patients were evaluated. Forty-five patients (25 male, 20 female) met the eligibility criteria (Figure 7), aged 12–18 years, and were randomized to three groups (n = 15 each): G1 (8 male, 7 female), G2 (10 male, 5 female), and G3 (7 male, 8 female). Mean ages were 16.8, 16.1, and 16.5 years for G1, G2, and G3, respectively. No significant differences were found in age between the groups ($P = .3669$; Table 1).

Number Analysis for Each Outcome

Quantitative root parallelism results for total evaluation of PR I were G1 = 7.04 ± 1.66, G2 = 7.77 ± 1.42, and G3 = 7.02 ± 0.99. No significant differences were found between the groups ($P = .2470$; Table 2). Analysis of the occlusal planes of the PRs revealed no significant differences (Table 3). Statistically significant differences between the right side (RS) and LS groups were observed in the mandibular posterior plane ($P = .001$; Table 4). PR II results were G1 = 2.33 ± 1.4, G2 = 2.8 ± 2.04, and G3 = 2.07 ± 1.49, with no significant differences among

Table 3. Panoramic Radiography (PR) I Segmented Analysis, Variability of Angular Measurements, and PRs According to Technique and Occlusal Planes[a]

	Bonding Type			
Variable	Direct (N = 15)	Indirect (N = 15)	Digital (N = 15)	P
SD PR I anterosuperior				.593
Mean ± DP	4.05 ± 1.1	3.86 ± 1	3.62 ± 1.32	
Median (min, max)	3.9 (1.9, 5.9)	4 (1.6, 6)	3.8 (1.5, 6.3)	
SD PR I posterosuperior				.171
Mean ± SD	4.95 ± 2.03	4.04 ± 1.56	3.89 ± 1.17	
Median (min, max)	5.4 (1.9, 8.1)	3.7 (1.8, 6.9)	3.6 (2, 5.8)	
SD PR I anteroinferior				.598
Mean ± SD	5.96 ± 2.99	6.16 ± 2.24	6.85 ± 2.19	
Median (min, max)	6.4 (1, 11.4)	6 (2.2, 10.6)	7.3 (2.6, 10.1)	
SD PR I posteroinferior				.591
Mean ± SD	7.94 ± 2.77	8.69 ± 2.34	7.88 ± 2.02	
Median (min, max)	7.6 (4.6, 13.6)	8.9 (5.3, 13.6)	7.6 (4.9, 12.4)	

[a] Analysis of variance. Show no significant differences between groups.

Table 4. Variability of Angular Measurements in Panoramic Radiography (PR) I Between Techniques and Bonding Sides[a]

Variable/Side	Bonding Type: Direct (N = 15)	Indirect (N = 15)	Digital (N = 15)	$P_{Bonding}$	P_{Side}	$P_{Interaction}$
SD PR I anteromaxillary				.923	.926	.782
RS						
Mean ± SD	3.23 ± 1.59	3.35 ± 0.96	3.51 ± 1.82			
Median (min, max)	3.2 (0, 5.2)	3.5 (1.8, 5.3)	3.5 (1, 6.7)			
LS						
Mean ± SD	3.56 ± 2.07	3.16 ± 1.78	3.26 ± 1.53			
Median (min, max)	3.2 (0.3, 8.3)	2.9 (0, 5.9)	2.7 (1, 5.9)			
SD PR I posteromaxillary				.647	.631	.248
RS						
Mean ± SD	3.44 ± 2.31	3.58 ± 2.25	3.87 ± 2.16			
Median (min, max)	2.5 (0.4, 7.4)	3.3 (0, 8.3)	3.2 (0.7, 7.7)			
LS						
Mean ± SD	4.14 ± 2.61	3.33 ± 1.4	2.77 ± 1.25			
Median (min, max)	3.7 (0.6, 10)	3.6 (1.1, 5.5)	2.7 (0.1, 4.6)			
SD PR I anteromandibular				.076	.142	.408
RS						
Mean ± SD	4.05 ± 1.78	4.34 ± 3.03	6.47 ± 2.99			
Median (min, max)	4.4 (0.6, 6.6)	4.4 (0.8, 13.2)	6.6 (0.9, 10.5)			
LS						
Mean ± SD	3.91 ± 2.83	3.93 ± 2.43	4.75 ± 3.32			
Median (min, max)	4.3 (0, 9)	3.9 (0.3, 8.1)	3.9 (0.2, 10.9)			
SD PR I posteromandibular				.482	.001[b]	.931
RS						
Mean ± SD	8.79 ± 4.21	9.67 ± 3.02	8.36 ± 3.6			
Median (min, max)	7.5 (0.3, 15.5)	10.5 (4.5, 15.2)	8 (3.4, 16.5)			
LS						
Mean ± SD	7.35 ± 2.85	7.74 ± 3.59	6.61 ± 2.04			
Median (min, max)	6.5 (3.4, 13.5)	7.1 (3.1, 13.6)	6.7 (3.1, 11.3)			

[a] LS indicates left side; RS, right side. Two-way repeated measures analysis of variance.
[b] Statistically significant difference in the posteromandibular plane on the RS.

groups ($P = .652$; Table 2) or between sides (Table 5). Quantitative analyses of marginal ridge leveling in DMs yielded G1 = 3.93 ± 1.33, G2 = 4.14 ± 1.29, and G3 = 3.25 ± 0.95, with no significant differences among groups ($P = .117$) or between sides. The ABO index of posterior marginal ridge leveling in PM was G1 = 1.47 ± 1.8, G2 = 1.4 ± 0.99, and G3 = 1.4 ± 0.99, with no significant differences among groups ($P = .989$) or between sides. Chair times were G1 = 56.7 ± 7.3 min, G2 = 52.8 ± 8.3 min, and G3 = 41.1 ± 11.8 min ($P < .001$; Table 2). Bonferroni multiple comparisons showed that G3 had a significantly shorter chair time than G1 or G2 (Table 6).

Harms

No serious harm was observed other than gingivitis associated with plaque accumulation.

DISCUSSION

Comparison of the accuracy between direct and indirect conventional bonding, CAD/CAM technology, and chair time remains a prominent focus in orthodontic research. In the present study, as Niu et al.[38] suggested, the G3 group used additive manufacturing or stereolithography to print the transfer tray, ensuring bracket placement accuracy and reproducibility, Duarte et al.[12] and Ciuffolo et al.[29] thereby characterizing a complete digital workflow.[1,2]

Precision was determined by evaluating root parallelism and marginal ridge height, key indicators of orthodontic treatment effectiveness. Authors of previous studies used PRs[33–37,39] and PMs to compare bonding techniques but did not cite the adjustment of arch bends or bracket replacement, which could have interfered with accuracy comparisons. In this study, the brackets were repositioned, if needed, only after the final images and models were collected. Some authors[40,41] suggested analyzing radiographic images and models before finishing the procedures; however, this analysis was performed after the final leveling phase. This timing is considered optimal for bracket repositioning, reducing the risk of errors and treatment time. Tooth position was assessed after at least 4 weeks of 18 × 0.025 CuNiTi arch expression.

Table 5. Variability in Panoramic Radiography (PR) II, in Plaster Models, According to Bonding Techniques[a]

Variable/Side	Bonding: Direct (N = 15)	Bonding: Indirect (N = 15)	Bonding: Digital (N = 15)	Total (N = 45)	$P_{bonding}$	P_{side}	$P_{Interaction}$
PR II					.666	.107	.542
RS							
Mean ± SD	1.47 ± 0.92	1.4 ± 1.24	1.33 ± 1.29	1.4 ± 1.14			
Median (min, max)	1 (0, 3)	1 (0, 4)	1 (0, 5)	1 (0, 5)			
LS							
Mean ± SD	0.6 ± 0.83	0.73 ± 0.7	0.6 ± 0.74	0.64 ± 0.74			
Median (min, max)	0 (0, 2)	1 (0, 2)	0 (0, 2)	0 (0, 2)			
Digital model					.110	.100	.880
RS							
Mean ± SD	2.09 ± 0.97	2.12 ± 0.88	1.73 ± 0.61	1.98 ± 0.83			
Median (min, max)	1.8 (0.8, 4.1)	1.8 (1.1, 3.8)	1.6 (0.9, 3.2)	1.8 (0.8, 4.1)			
LS							
Mean ± SD	1.85 ± 0.5	2.02 ± 0.65	1.52 ± 0.56	1.8 ± 0.59			
Median (min, max)	1.9 (0.9, 2.7)	1.9 (1.2, 3.5)	1.5 (0.6, 2.5)	1.7 (0.6, 3.5)			
Plastic Model					.842	.183	.360
RS							
Mean ± SD	1.07 ± 1.1	0.67 ± 0.72	0.8 ± 0.68	0.84 ± 0.85			
Median (min, max)	1 (0, 3)	1 (0, 2)	1 (0, 2)	1 (0, 3)			
LS							
Mean ± SD	0.6 ± 0.83	0.73 ± 0.7	0.6 ± 0.74	0.64 ± 0.74			
Median (min, max)	0 (0, 2)	1 (0, 2)	0 (0, 2)	0 (0, 2)			

[a] LS indicates left side; RS, right side. Two-way repeated measures analysis of variance; GEE (Generalized Estimation Equation) with Poisson distribution and identity link function with symmetrical component correlation between sides. Shows no significant differences between the groups.

The measurements used were the two parameters of the ABO method: root parallelism and marginal ridge height. To assess root parallelism, two methods were employed: the quantitative angular method (PR I) and the visual method (PR II). Lucchesi et al.[42] highlighted inconsistencies and low accuracy in visual interpretation (PR II), necessitating further research, including the present study. Some authors advocated angular measurements using the PR; however, authors of previous studies used a single reference plane and did not consider potential distortions in the canine region. Disagreement persists in the reference plane for the root parallelism analysis.[43–48] To mitigate distortion, especially in the anterior region, three planes were used: one anterior and two posterior. This approach minimized distortions.[49,50] Comparing the posterior marginal ridge heights among bonding methods, these were found to be achieved qualitatively in PMs and quantitatively in DMs. The heights between the lower first and second premolars were examined to account for anatomical variations. Statistical analysis showed no significant differences in the marginal ridge heights among the bonding methods for either PMs ($P = .989$) or DMs ($P = .117$; Table 2). Consistent with previous trials,[27,33–35] G3 showed superior but not significantly different results in the ridge-leveling and linear analyses. This agreed with the findings of Hartsfield and Crane,[51] who linked ridge leveling with reduced root angulation errors.

In the study by Aguirre et al.,[23] DB was more effective on the RS of the maxillary arch, with no significant differences in IB. DB favored the LS in the lower arch. At the same time, IB also positioned the brackets better on the LS. Using the PR I method (Table 4), lower variability was found in root inclination in the LS posteromandibular region than in the RS ($P < .001$), regardless of the bonding method. However, the PR II method showed no statistical differences in the DMs and PMs when segmented by side (Table 5), likely because of the sensitivity of PR I in detecting root angulation.

Table 6. Multiple Comparisons Among Groups for Chair Time[a]

Variable	Comparison	Mean Difference	Standard Error	P	95% Confidence Interval: Inferior	95% Confidence Interval: Superior
Chair time (min)	G1-G2	3.87	3.41	.788	−4.62	12.36
	G1-G3	15.60	3.41	<.001[b]	7.11	24.09
	G2-G3	11.73	3.41	.004[b]	3.24	20.22

[a] Bonferroni multiple comparisons.
[b] The average chair time was significantly lower in indirect digital bonding than in other techniques ($P < .05$).

Authors of recent studies[23,33–35] comparing bracket bonding did not assess chair time but focused on the total treatment time for each group, G3 showed the shortest chair time, likely due to differences in tray segmentation. The G2 tray was segmented into three parts (one anterior and two posterior) to minimize errors, whereas G3 was divided into two hemiarcs (RS and LS) as suggested by the manufacturer, a design that favored bonding and minimized failures. The findings in the current study support the initial null hypothesis that no difference in accuracy would be found between DB, IB, and indirect digital CAD/CAM, although the numerical results favored G3.

Limitations

Blinding during the intervention was not feasible. However, the results were evaluated blindly, reducing the risk of bias. Segmentation of the trays was performed to minimize bonding failure rates, representing a minor study limitation in chair-time measurements.

Generalizability

The findings may be limited in generalizability, as the study was conducted at a single center by a single proficient clinician skilled in DB and IB techniques.

CONCLUSIONS

- All three bonding methods showed treatment success.
- The CAD/CAM group had significantly shorter chair times indicating that, while its accuracy matched that of conventional methods, it offered the added benefit of reduced chair time, enhancing both patient and professional experience.

DISCLOSURE

No funding or conflict of interest was declared.

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