ORIGINAL ARTICLE

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Accuracy of 3-dimensional–printed customized transfer tray using a flash-free adhesive system in digital indirect bonding: An in vivo study

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Introduction: This paper evaluated the accuracy of a computer-aided design and manufacturing indirect bonding technique using a new customized 3D-printed transfer tray and a flash-free adhesive system for orthodontic bonding. **Methods:** This in vivo study analyzed 106 teeth selected from 9 patients undergoing orthodontic treatment. Quantitative deviation analysis was performed to evaluate the bonding positioning errors, assessing the differences between the virtually planned and the clinically transferred bracket position after indirect bonding procedures by superimposing 3-dimensional dental scans. Estimated marginal means were evaluated for individual brackets and tubes, arch sectors, and overall collected measurements. **Results:** A total of 86 brackets and 20 buccal tubes were analyzed. Among individual teeth, mandibular second molars showed the highest positioning errors, whereas maxillary incisors reported the lowest values. Considering arch sectors, the posterior areas showed greater displacements than the anterior areas, as the right side compared to the left side, with a higher error rate reported for the mandibular arch than the maxillary arch. The overall bonding inaccuracy measurement was 0.35 mm, below the clinical acceptability limit of 0.50 mm. **Conclusions:** The accuracy of a 3-dimensional-printed customized transfer tray using a flash-free adhesive system in computer-aided design and manufacturing indirect bonding was generally high, with greater positioning errors for posterior teeth. (Am J Orthod Dentofacial Orthop 2023;164:505-15)

Since the introduction of preadjusted appliances, accurate bracket placement has become a key factor for a successful orthodontic treatment to achieve the ideal dental position during the final phase of therapy.[1] Frequently, orthodontic brackets are directly positioned on dental crowns (direct bonding),[2] but many orthodontists prefer indirect bonding for its greater accuracy.[3]

The indirect bonding technique was first described in 1972 by Silverman et al,[4] and over the years, it has been reported that this method could reduce chair time[5] and overall treatment time,[6] improving the patient's comfort.[7] In the traditional indirect bonding, brackets are positioned on plaster models and then transferred to the teeth through transfer trays by a laboratory process.[2] Although indirect technique could reduce the positioning errors because of clinical variables (low visibility, limited mouth opening, excessive salivary flow or complex dental morphology),[8,9] the traditional laboratory steps could induce many errors related to the inner technical procedures or the professional experience of the operator.[10,11] The manual bonding of brackets on models or the use of conventional materials could influence the bracket placement, reducing the accuracy of the trays during their fabrication, transfer, and removal.[11,12]

Computer-aided design and manufacturing (CAD-CAM) technology has recently been introduced for indirect bonding,[5,13] as an alternative to the traditional method.[5,9] Among its advantages, this digital process

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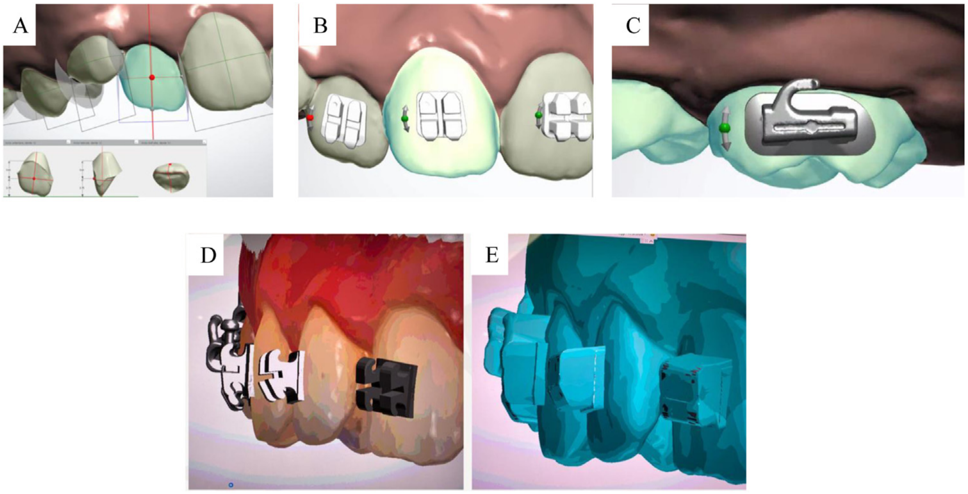

Fig 1. Segmentation of maxillary arch and virtual bracket positioning in Ortho Analyzer software: **A,** On virtual models, reference lines and points were drawn on each tooth and visualized on frontal, lateral and occlusal view; **B** and **C,** Virtual placement of brackets and buccal tubes; **D,** Stereolithography file of positioned brackets; **E,** Stereolithography file of boxed brackets.

enables virtual planning of the bracket position on digital models and designing and fabricating customized 3-dimensional (3D) printed devices to transfer the virtual planned bracket position to the teeth.[11,14-16]

In the past few years, several CAD-CAM indirect bonding systems have been proposed and satisfactory results have been reported for the effectiveness and efficiency of the digital indirect approach.[17,18] However, only a few studies have evaluated in vivo the accuracy of virtual bonding in the oral cavity using 3D-printed transfer trays[16,19,20] because most of the available studies have been performed in vitro on experimental dental casts.[9-11,13,21-25]

Therefore, this study aimed to describe a fully digital workflow for CAD-CAM indirect bonding (from the planning to the manufacturing) and to evaluate in vivo the accuracy of bracket position using a new 3D-printed customized transfer tray and a flash-free adhesive system for orthodontic bonding.

MATERIAL AND METHODS

Nine consecutive patients seeking orthodontic treatment at the section of Orthodontics, Department of Dentistry, University of San Raffaele, were enrolled. The inclusion criteria were permanent dentition and fully erupted teeth (except third molars). The exclusion criteria were systemic or local diseases, malformations or excessive rotations of dental crowns. All patients received orthodontic treatment with a fixed ceramic appliance, according to their treatment needs. All the procedures of this research have adhered to the Declaration of Helsinki. A written consent was signed by each patient to adhere to the protocol of this study.

Digital impressions of dental arches were acquired with a TRIOS 3 color intraoral scanner (3Shape, Copenhagen, Denmark) and imported and prepared in OrthoAnalyzer software (3Shape) for segmentation of the tooth units (Fig 1, *A*). An ovoid arch form (Orthoform III) was chosen, and ceramic orthodontic brackets (3M Clarity Advanced Ceramic Brackets, MBT slot 0.022-inch; 3M Unitek, Monrovia, Calif) and buccal tubes (3M Victory Series Superior Fit Buccal Tubes, MBT slot 0.022-inch; 3M Unitek) were then selected from the virtual software library. According to the MBT height positioning method, brackets and tubes were virtually bonded from incisors to second molars (Figs 1, *B* and *C*). Then, a single experienced orthodontist with 20 years of orthodontic experience (G.F.) controlled their 3D position, interacting with the software remotely via TeamViewer (TeamViewer GmbH, Goppingen, Germany).

After the orthodontist's adjustments, the virtual model with brackets (model 1 [M1]) was exported, and the digital transfer tray was planned by the technician.

The M1 was imported in Appliance Designer software (3Shape, Copenhagen, Denmark) (Fig 1, *D*), and the virtual brackets were modified into boxed brackets, which corresponded to the bracket forms without the

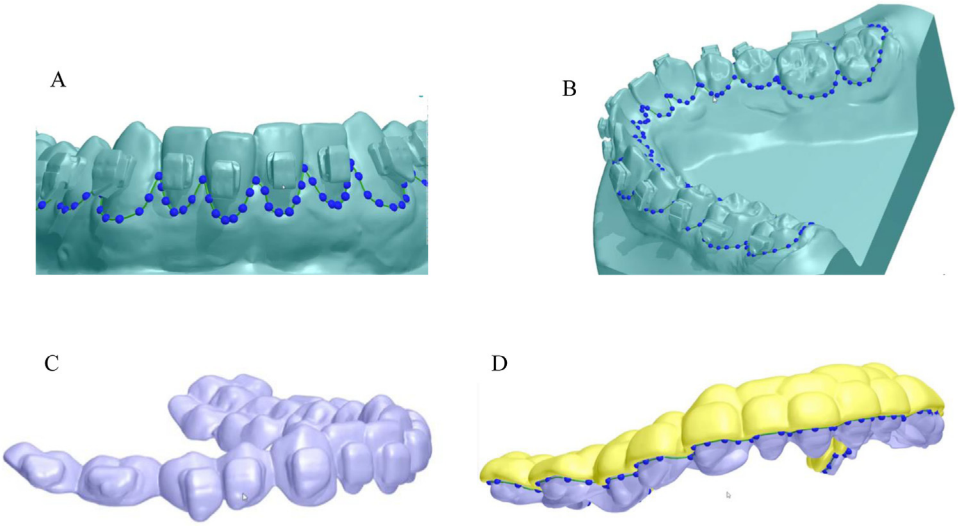

Fig 2. Design of double-thickness transfer tray for the mandibular arch, in Appliance Designer software: **A** and **B,** Design of the first layer, from buccal and lingual view; **C,** In *purple*, the first thinner layer is shown, covering the entire bracket and dental surfaces, from buccal to lingual/palatal sulcus; **D,** In *yellow*, the second thicker layer is added, covering the bracket surfaces, but not extending in the third gingival of the teeth.

undercuts around the brackets and tubes, to eliminate any possible undercuts in the transfer tray (Fig 1, *E*).

Then, a digital transfer tray was designed in 2 parts: using the create a shell command (a shell is a wraparound surface with a fixed thickness and offset distance defined by the user) and setting the shell thickness to 1 mm and the offset of 0.01 mm, the first layer of the tray was designed, covering the entire surfaces of the brackets and of the teeth from buccal to lingual/palatal sulcus (Figs 2, *A-C*); a second thicker layer was then added, extending until the brackets and tubes (not beyond the teeth middle third), setting the shell thickness of 1.5 mm and the offset of 0 mm (Fig 2, *D*). These 2 layers were combined in a unique customized double-thickness structure and exported in stereolithography file format.

After importing the stereolithography file on PreForm print preparation software (Formlabs Inc, Somerville, Mass), the biocompatible light-curable flexible 80A resin (Formlabs Inc) was used to manufacture the transfer tray with the desktop 3D printer (Formlabs Inc) (Fig 3, *A*).

The printing orientation of the trays on the build platform was 45°, as reported by the print recommendations of the manufacturer and as confirmed by previous studies.[26,27] The trays were removed from the build platform and washed with isopropyl alcohol in 2 cycles of 10 minutes each using the Form Wash (Formlabs Inc), according to the recommended Form Wash time settings. After ensuring the liquid resin was washed off completely, the trays were left to dry completely before postcuring. Then, the trays were postcured for 15 minutes at 60°C using Form Cure (Formlabs Inc), according to the recommended Form Cure time and temperature settings, to reach the optimal mechanical properties of the flexible 80A resin.

Brackets and tubes were accurately placed in the customized transfer trays through a dental plier, using light pressure until the complete fit of each bracket in its respective space in the tray was obtained (Fig 3, *B*). Then, transfer trays were delivered to the orthodontist. All indirect bondings were performed by the same experienced right-handed orthodontist (G.F). After placing a cheek retractor to isolate the teeth, their buccal surfaces were etched with 37% phosphoric acid for 30 seconds, rinsed with water for 30 seconds, air-dried and primed using a light-cure adhesive primer (Transbond XT Light Cure Adhesive Primer, 3M Unitek).

Each tooth was then bonded with adhesive-precoated ceramic brackets and metallic tubes using a system with a flash-free adhesive (APC Flash-Free Adhesive Coated Appliance System, 3M Unitek) to standardize the bonding procedures. After the indirect bonding (Fig 3, *C*), brackets were light-cured for 20 seconds, then the tray was removed, and a new 3D digital impression (model 2 [M2]) was immediately acquired.

This scan was performed by the same operator with a standardized protocol. The scan started from the

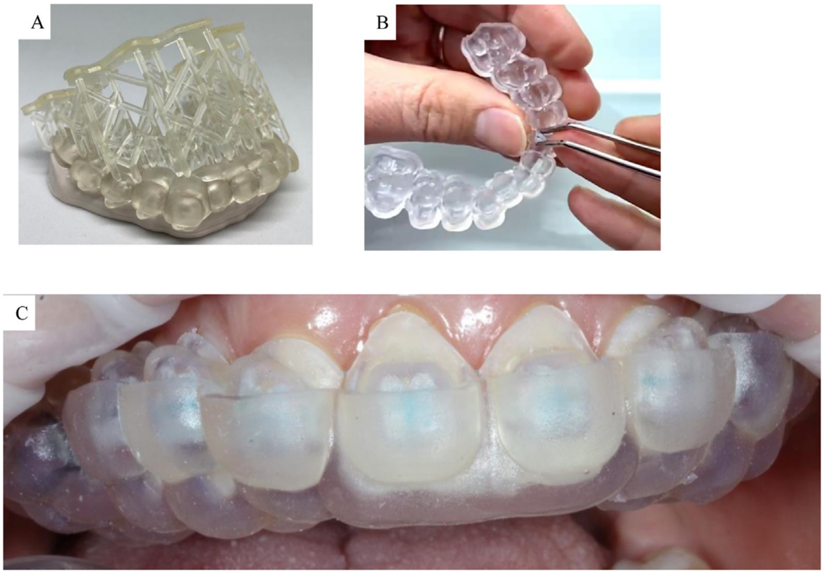

Fig 3. 3D-printed transfer tray: **A,** After the 3D printing process; **B,** During bracket placement; **C,** In the mouth, with positioned brackets.

occlusal surfaces of the molars from the right to the left side; then the buccal and lingual/palatal surfaces were recorded. Brackets and tubes were scanned to register their entire surfaces, reducing the risk of distortion.

Data from M1, with the virtually planned bracket position, and data from M2, with the actual transferred bracket position, were superimposed in GOM inspect 2020 (GOM Software 2020; GOM GmbH, Braunschweig, Germany). Because there were no dental movements between M1 and M2, the regions of the dental crowns without brackets or tubes were selected to perform superimposition. A preliminary point-based superimposition was performed, selecting 3 equivalent points on each arch of M1 and M2 (generally 1 on the incisal edge and 2 on the molar buccal cusps). Then, the software sets a best-fit alignment based on the automated best-fit algorithm.

Subsequently, quantitative analysis was conducted to evaluate the superimposed M1 and M2 accuracy.

For the quantitative analysis of the bonding displacements, 12 points were manually selected for each bracket (Figs 4, *A-C*) and 8 for each tube (Figs 4, *D-F*), including frontal, mesial and distal landmarks to obtain an accurate assessment of brackets and tubes in all direction. To minimize random and systematic errors,[8,28] all points were marked by the same experienced operator (G.F.).

The 12 points analyzed for brackets included 6 on the buccal side (3 on the mesial and 3 on the distal wings) (Fig 4, *A*), 3 on the mesial side (Fig 4, *B*), and 3 on the distal side (Fig 4, *C*).

The 8 points evaluated for tubes included 4 on the buccal side (2 on the mesial and 2 on the distal edges) (Fig 4, *D*), 2 on the mesial side (Fig 4, *E)*, and 2 on the distal side (Fig 4, *F*).

On superimposed models, the distances between these points were assessed through a deviation analysis, as previously reported.[28,29] The calculation of these point-to-point distances between M1 and M2 were automatically converted to root mean square (RMS) values that evaluated the mean value of errors when comparing 2 datasets with an identical coordinate system. The RMS values indicated the data of accuracy, calculating the numerical extent of matching or mismatching on the basis of the model used as a reference for the deviation analysis. This study assessed the point-to-point distance calculation by choosing M1 as the reference (reference model) on which M2 (test model) was superimposed and from which the distances were calculated.[30]

Therefore, for each corresponding point on brackets and tubes, numerical differences were computed by the software, setting millimeters as the standard unit. These values, designed by a positive or negative sign, described the amount and the direction of transfer discrepancy. A positive value indicated greater exposure of the M2, whereas a negative value indicated a higher exposure of the M1 on superimposition.

Statistical analysis

Fifteen days after the initial measurements, the experienced operator repeated 40 measurements on

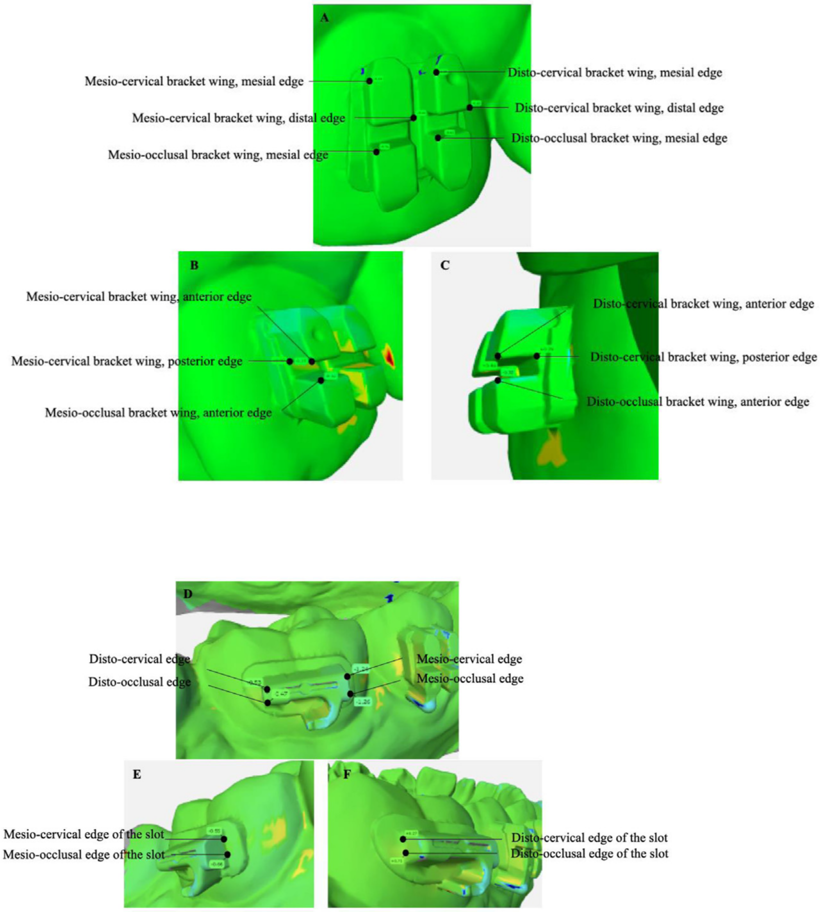

Fig 4. Superimposition and quantitative analysis of the bonding inaccuracy using GOM inspect software. For each bracket, 12 points were analyzed: **A,** 6 on the buccal view; **B,** 3 on the mesial view; **C,** 3 on the distal view. For each tube, 8 points were analyzed: **D,** 4 on the buccal view; **E,** 2 on the mesial view; **F,** 2 on the distal view.

randomly selected superimposed models. Intraexaminer reliability was assessed using the intraclass correlation coefficient (model: 2-way mixed effects; type: single measurement; definition: absolute agreement).

Only absolute values for each measurement were considered to avoid the possibility that the sum of positive and negative discrepancy values would negate one another.

From the RMS values of each bracket and tube, estimated marginal means (EMMs) were calculated for individual teeth. The EMMs, corrected for possible confounding factors, were expressed using a generalized linear model, including the random effect on patient and point, to account for possible sample dependencies and imbalances.

Then, EMMs were computed for the arch sector, considering each maxillary and mandibular arch divided into 3 areas (anterior, right posterior and left posterior sectors, respectively).

The overall EMMs of the total sample were also calculated from all collected data, resulting in a generalized discrepancy number of the present technique. Statistical analysis was performed by R software (version 4.1.0; R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

One hundred and six teeth (86 brackets and 20 buccal tubes) were analyzed. The intraclass correlation coefficient test showed an excellent correlation (0.994) which ranged from 0.989 to 0.997 for intraobserver reliability.

The results of the collected data are shown in Tables I-III. The results showed EMMs obtained with a

Table I. Quantitative measurements of bonding discrepancy, calculated for each tooth and expressed in millimeters

Tooth	*EMM*	*SE*	*Df*	*95% Confidence level*
Maxillary				
Right central incisor	0.268	0.046	65.303	0.177-0.359
Right lateral incisor	0.243	0.051	99.959	0.141-0.344
Right canine	0.365	0.046	65.303	0.274-0.456
Right first premolar	0.327	0.051	98.521	0.226-0.429
Right second premolar	0.288	0.046	65.303	0.197-0.379
Right first molar	0.633	0.060	178.420	0.514-0.752
Right second molar	0.312	0.010	683.717	0.118-0.507
Left central incisor	0.233	0.046	65.303	0.141-0.324
Left lateral incisor	0.268	0.051	99.958	0.167-0.370
Left canine	0.270	0.046	65.303	0.179-0.362
Left first premolar	0.329	0.051	98.520	0.227-0.430
Left second premolar	0.342	0.046	65.303	0.251-0.433
Left first molar	0.420	0.060	178.419	0.301-0.539
Left second molar	0.526	0.010	683.718	0.332-0.720
Mandibular				
Left central incisor	0.284	0.041	47.802	0.200-0.369
Left lateral incisor	0.322	0.041	47.802	0.238-0.407
Left canine	0.362	0.041	47.802	0.277-0.446
Left first premolar	0.323	0.041	47.802	0.238-0.407
Left second premolar	0.311	0.041	47.802	0.227-0.395
Left first molar	0.322	0.049	84.905	0.225-0.419
Left second molar	0.750	0.100	637.990	0.553-0.947
Right central incisor	0.280	0.042	47.801	0.195-0.364
Right lateral incisor	0.347	0.041	47.801	0.263-0.431
Right canine	0.308	0.041	47.801	0.224-0.392
Right first premolar	0.438	0.041	47.801	0.353-0.522
Right second premolar	0.345	0.041	47.801	0.260-0.429
Right first molar	0.478	0.049	84.905	0.380-0.574
Right second molar	1.371	0.100	637.990	1.175-1.568

EMM, estimated marginal mean; *SE*, standard error; *Df*, degrees of freedom.

Table II. Quantitative measurements of bonding discrepancy, calculated for arch sectors and expressed in millimeters

Sector	*EEM*	*SE*	*Df*	*95% Confidence level*
Mandibular anterior[†]	0.308	0.037	8.332	0.224-0.392
Mandibular right posterior[‡]	0.415	0.037	8.574	0.332-0.499
Mandibular left posterior[§]	0.342	0.037	8.574	0.258-0.426
Maxillary anterior[||]	0.265	0.039	10.540	0.179-0.350
Maxillary right posterior[¶]	0.380	0.040	10.782	0.294-0.466
Maxillary left posterior[#]	0.348	0.040	10.782	0.261-0.434

EMM, estimated marginal mean; *SE*, standard error; *Df*, degrees of freedom.
[†] From right to left lateral incisors of the mandibular arch; [‡] From right canine to right second molar of the mandibular arch; [§] From left canine to left second molar of the mandibular arch; [||] From right to left lateral incisors of the maxillary arch; [¶] From right canine to right second molar of the maxillary arch; [#] From left canine to left second molar of the maxillary arch.

mixed-effects model to consider possible data dependencies corresponding to the same patient and/or position.

The quantitative results for each bracket/tube showed a progressive increase of displacements toward the posterior zones, as reported in Table I.

The highest error rate was found at the level of the mandibular second molars (mandibular left second molar, 0.750 mm; mandibular right second molar, 1.371 mm), whereas the lowest errors were shown in the placement of the maxillary incisors (maxillary right central incisor, 0.268 mm; maxillary right lateral incisor, 0.243 mm; maxillary left central incisor, 0.233 mm; maxillary left lateral incisor, 0.268 mm).

The quantitative results for arch sectors also confirmed the same trend in the statistical distribution

Table III. Quantitative measurements of the overall bonding discrepancy, expressed in millimeters

Measurement	*EMM*	*SE*	*Df*	*95% Confidence level*
Overall	0.346	0.034	5.227	0.259-0.432

EMM, estimated marginal mean; *SE*, standard error; *Df*, degrees of freedom.

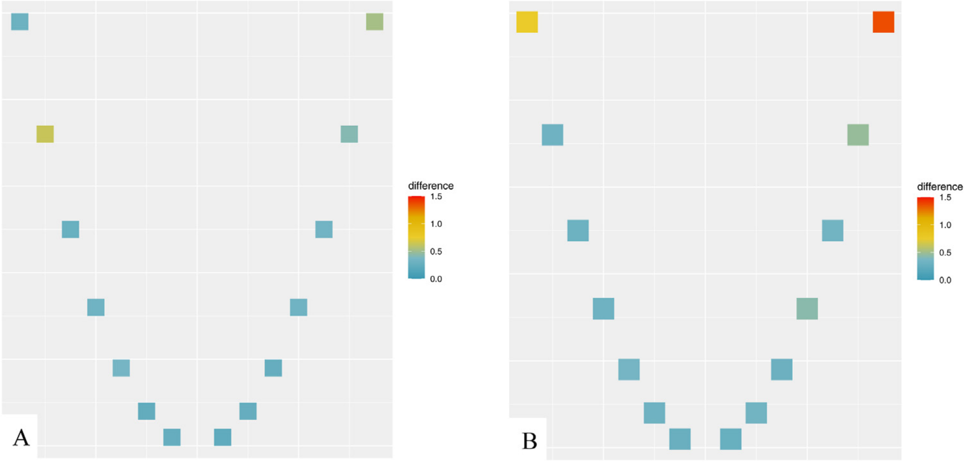

Fig 5. A graphic representation of the EMMs for the maxillary **(A)** and mandibular **(B)** arch. Each square corresponds to a bracket or tube. *EMMs,* estimated marginal means.

of discrepancies (Table II). The mandibular arch showed greater placement discrepancy than the maxillary arch (Table II). In both arches, the posterior sectors showed higher positioning errors than the anterior ones and the left side compared with the right (Table II).

The means of the overall bonding inaccuracy was 0.346 mm (Table III).

A graphic representation of the EMMs was also performed for the maxillary (Fig 5, *A*) and the mandibular arch (Fig 5, *B*).

DISCUSSION

The accuracy of bonding position is defined by the absence of discrepancy in the transferred position of orthodontic brackets compared with their virtual planned placement.[8]

This study evaluated the accuracy of a fully CAD-CAM indirect bonding technique using a new 3D-printed transfer tray and a flash-free adhesive system on 3D superimposed scans.

In literature, different types of transfer devices have been proposed on the basis of the digital approach.[16] Trays can be fabricated after 3D-printing a model with virtual planned brackets, using conventional materials such as silicone or thermoplastic materials, or can be virtually designed and directly manufactured by the 3D-printing process.[16]

Several in vitro studies have reported the accuracy of 3D-printed trays fabricated with CAD-CAM technology compared with conventional systems.[10,11,22,25,31] In addition to time and cost saving,[5] the use of 3D-printed trays seems to minimize human error during laboratory steps, increasing the fit of the trays on teeth compared with traditional handwork and improving the precision of the indirect bonding.[13]

Duarte et al[9] found no significant differences between the digital plan and the bonded brackets when using 3D-printed trays, also concluding that the digital libraries of both conventional and self-ligating brackets could be considered accurate and reproducible for the digital indirect bonding. Therefore, although the digital library images of the brackets seem not to influence the accuracy of the CAD-CAM indirect bonding, the selection of 3D-printed materials, the design options of the tray, and the clinical bonding procedures are critical variables that may influence it.[31,32]

Jungbauer et al[22] reported that, in vitro, hard printing materials could affect the transfer tray accuracy more than soft materials. Nevertheless, although hard materials could induce an incomplete fit of the tray on teeth[9] or immediate bracket debonding during tray removal,[5] elastic properties could lead to distortion of the tray under finger pressure of the clinician, with consequent tray over seating and bracket placement errors.[9]

In this technique, the material used for 3D printing was a biocompatible light-curable resin, an elastomeric resin that enables the printing of hard but flexible structures on the basis of their thickness.

The tray was designed as a customized double-thickness structure, combining differential thickness within the tray, which gave it additional rigid-elastic properties. The more flexible part of the tray (because of its reduced thickness of 1 mm) covered the entire dental surface, including brackets and tube, to make its removal easier after indirect bonding. The hardest part (1.5 mm of thickness) was designed to provide stability and precise control of the brackets during tray positioning. This thicker layer covered the bracket surfaces but not extending beyond the middle third of the teeth to guarantee appropriate retention of the brackets in the tray during transfer while reducing the risk of debonding during its removal. In addition, the tray was designed by an Appliance Designer removing the undercut on the brackets and with an offset of only 0.01 mm to reduce the rate of immediate bonding failures, maintaining, at the same time, the exact dimensions of the brackets and providing sufficient retention for their positioning, as reported by literature.[5]

Because the amount of adhesive applied to brackets and teeth during the clinical bonding procedures has been reported to induce bonding errors or gaps,[16,33] as suggested by Chaudary et al,[19] in this study adhesive-precoated ceramic brackets and metallic tubes using a system with a flash-free adhesive were used to standardize the thickness of the bonding materials on each tooth and each patient,[19] and to avoid the excess of adhesive flash around the brackets and the contact surfaces.[16]

Furthermore, the characteristic transparency of the 3D-printed resin permitted the visual check of the tray fit, especially on posterior areas, as well as the brackets polymerization, allowing a complete penetration of the curing light through the transfer tray and avoiding the immediate bonding failures with consequent additional costs,[13] which are the most common disadvantages of indirect bonding reported in the literature.[2,5,34]

Over the years, the precision of the methods for measuring the accuracy of indirect bonding has greatly increased because of the improvements in the available 3D superimposition software.[23] Previously, the positioning errors were analyzed on 2-dimensional photographs, with inaccurate and limited results based on the operator's sensitivity.[13,23]

Recently, 3D images superimposition has replaced the 2-dimensional technique, and a large number of available 3D methods have been proposed in the literature to evaluate the accuracy of bracket positioning in the CAD-CAM indirect system.[23]

Grünheid et al[33] used a cone-beam computed tomography to capture 3D positioning data in vitro, reporting a numeric value of bracket accuracy <0.1 mm. Although the superimpositions of cone-beam computed tomography data minimized the measurement errors, a considerable radiation rate must be considered in vivo.

Most studies performed a matching of the model scans in vitro[11,13,14,22,23,35] or intraoral scans in vivo,[16,19] using a 3D superimposition software that analyzed the positioning differences in a local coordinate system, assessing linear (mesiodistal, vertical, and buccolingual) and angular (torque) measurements.

Kim et al[13] showed an acceptable accuracy in vitro by model scans superimposition, reporting a maximum linear error of 0.71 mm for the posterior teeth with high cusps.

Niu et al[11] did not report in vitro higher positioning errors in posterior teeth compared with the anterior, in contrast to Park et al[14] in which molars showed the maximum positioning discrepancy.

In vivo, the scans of dental arches have a reduced quality compared with the scans of models, especially when brackets are bonded on teeth[13,17]: the limited space and saliva reduce the scanner sensitivity in distal areas, such as a longer scan time or a different scanning pattern increase the number of acquisition errors.[36,37]

De Oliveira et al[9] found that errors were more significant in the posterior teeth, although the frequency of errors was lower in indirect bonding than in the direct system.

This study found a greater positioning discrepancy for molars, especially on the left side. Although a standardized scanning procedure was used to reduce errors and avoid interference of salivary and soft tissues, scanning the posterior region requires more raw data than the anterior area, which needs an increased scan time.[38] These factors and the lower lighting conditions during the posterior region scanning procedure could contribute to the higher number of acquisition errors in the posterior region observed in this study.[38]

Moon et al[39] found that the scanning errors tend to be greater on the opposite side to the start of the scan, concluding that the scanning direction may also be a factor in the differences between the left and right sides. In this study, the scanner started to move from the right side to the left as the right-handedness of the operator, contributing to the higher transfer error found on the left side and in the posterior area.

Although the scanner used in this study was one of the most accurate available on the market with a precision of 4.5 ± 0.9 μm and trueness of 6.9 ± 0.9 μm,[40] the effect of brackets bonded to tooth surfaces can induce an image distortion because of the scattered reflection of light rays by the brackets in the mouth during scanning.[41] The authors used a ceramic bracket system for premolars, canines and incisors to reduce this error because the ceramic surfaces have shown a lower discrepancy than metallic surfaces.[42] In contrast, metallic tubes were used for molars, and this difference could also explain their highest positioning errors compared with the other teeth.

In contrast to Xue et al,[16] in which the matching was done on bracket surfaces, in this study, the matching of the scans M1 and M2 has performed on teeth surfaces because of their stability to improve the accuracy of the superimposition.[32,41] An alternative superimposition method would have been to match the crowns of individual teeth, excluding the brackets/tubes.[32,35] However, as reported by previous studies,[17,25] unclear data on proximal surfaces in crowded teeth may lead to recording an empty digital image, inducing measurement errors during superimposition. Therefore, as reported by Moon et al,[39] in this study, the scans were superimposed, selecting 3 corresponding reference points (incisal midpoint and mesiobuccal cups of the right and left first molars), after which the automatic best-fit alignment was employed to finalize the matches.

In the previous in vivo studies,[16,19,20] bracket position errors were analyzed quantitatively, setting a coordinate system to measure the linear differences between the virtual and the transferred bracket position. The signs (positive or negative) of the values expressed the direction of bonding displacement in relation to the reference position of each coordinate.[16,19]

In this study, the authors used the digital analysis deviation to calculate quantitative discrepancies between the surface points of 2 superimposed models[28,43] because digital superimposition provides more accurate and reliable data than linear measurements, as previously reported in the literature.[44]

Moreover, according to Bachour et al,[20] which considered the numerical differences in their absolute values, in this study, the accuracy discrepancy was estimated using RMS values because this parameter is less influenced by the offset errors (such as a lower sensitivity of the results because of the compensation between positive and negative values) compared with linear difference measurements.[28,45]

In addition, as confirmed by the high repeatability of the method, the landmarks used in this study may be considered reproducible reference points, allowing the examiner to have the same standard view for the measurements and to obtain an accurate analysis of bracket position in any direction.[9,19,46]

Subsequently, the means of the recorded RMS values were computed using the EMM approach, which allows for estimating specific main factors or factor combinations in a generalized linear model and, optionally, comparisons or contrasts among them (keeping into account possible dependencies among measurements).

After EEMs calculation, a single mean value of bonding inaccuracy was obtained, indicating the generalized positioning errors for each tooth type, arch sector, and the total sample.

In this way, considering the systematic errors during scanning, processing and matching of 3D scans, which could affect the quality of the recorded data,[36] the authors evaluated the overall clinical acceptability of the present CAD-CAM indirect bonding technique, assessing whether using 3D-printed double-layer transfer tray and a flash-free adhesive system, the transfer accuracy was within the accepted professional standards, on the basis of American Board of Orthodontics objective grading system.[47]

Positioning errors may affect treatment goals, and literature reported that errors less than 0.5 mm are considered clinically acceptable, but over this value, teeth alignment and positioning of marginal ridges could be negatively influenced.[47] In this study, the 3D overall inaccuracy was 0.346 mm. The greater bonding errors were reported only for some molars (maxillary right first molar, maxillary left second molar, and mandibular right and left second molars) that were >0.5 mm. In contrast, the other mean errors were within clinically acceptable limits (<0.5 mm).

Based on these results, the proposed indirect bonding technique resulted in accuracy for bracket positioning.

A potential limitation of this protocol was that the method used for quantitative analysis does not provide insight into the magnitude of linear (occlusogingival, buccolingual, mesiodistal) and angular (torque, tip and rotation) placement deviations that may affect the movement of the associated tooth.

Further studies should be conducted to assess the reproducibility of the procedure by various operators with different clinical skills.

CONCLUSIONS

A digital indirect bonding technique based on a new 3D-printed customized transfer tray using a flash-free adhesive system was proposed, and its 3D accuracy was evaluated in vivo, leading to the following conclusions:

1. Second molars were the teeth with the highest bonding errors, whereas incisors showed the lowest error rate.
2. Posterior sectors showed higher positioning errors than the anterior ones, but the bonding discrepancy of each arch sector was within clinically acceptable limits.
3. The mandibular arch showed greater bonding errors than the maxillary arch.
4. The 3D overall accuracy was generally high.

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AUTHOR CREDIT STATEMENT

Gianluigi Fiorillo contributed to conceptualization, methodology, and formal analysis; Alessandra Campobasso contributed to original manuscript preparation; Giulia Caldara contributed to conceptualization, methodology, and formal analysis; Giovanni Battista contributed to original manuscript preparation; Eleonora Lo Muzio contributed to manuscript review and editing; Gualtiero Mandelli contributed to manuscript review and editing; Alessandro Ambrosi contributed to conceptualization, methodology, and formal analysis; Giorgio Gastaldi contributed to manuscript review and editing.

SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ajodo.2023.02.017.

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