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Assessment of the Accuracy of Bracket Positioning Using Two Different Materials for the Construction of the Indirect Bonding Tray

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Abstract

Objective: To assess the accuracy of bracket positioning using two different materials for the construction of indirect bonding trays. **Materials and Methods:** A randomized controlled trial was conducted on 20 patients (200 brackets) divided into two groups. Group A used indirect bonding trays made of transparent flexible silicone (Memosil 2), while Group B used trays made of double-layer thermoformed sheets. Upper teeth (from right to left second premolars) were bonded, excluding molar tubes. Virtual bracket positioning was performed using digital scans and 3D-printed models. Post-bonding accuracy was evaluated by superimposing pre- and post-treatment models and measuring deviations in vertical (occluso-gingival) and horizontal (mesio-distal) directions. **Results:** Thermoformed trays demonstrated superior vertical accuracy compared to silicone trays. Conversely, silicone trays showed better horizontal accuracy. All measured deviations were clinically acceptable (<0.5 mm). Statistical analysis revealed significant differences between the groups ($p < 0.05$). **Conclusion:** The choice of tray material influences bracket positioning accuracy, with thermoformed trays excelling in vertical precision and silicone trays performing better horizontally. Clinicians should consider these trade-offs when selecting tray materials for indirect bonding. Digital workflows enhance reproducibility, supporting their adoption in orthodontic practice.

Keywords: Indirect bonding, bracket positioning, silicone trays, thermoformed trays, digital orthodontics.

Introduction

The brackets are the main constituent of fixed orthodontic therapy used in the treatment of various malocclusions. To achieve the best results possible, using the straight wire technique, an accurate bracket positioning is required to precisely express the built-in prescriptions of bracket systems available in the market. However, in the direct bonding technique, it’s challenging to consistently place the brackets in their optimal position. Consequently, wire bending at the finishing stage is often necessary to obtain the desired results.

It is evident today that the future of orthodontics will primarily rely on digital orthodontics. By utilizing indirect bonding trays, brackets can be accurately transferred to the tooth surface and orthodontists can achieve the best possible results for both patients and themselves.

Nowadays, different techniques of indirect bonding are used. However, the accuracy of the results maybe questionable. Accordingly, the study was conducted to assess the accuracy of bracket positioning using two different materials for the construction of the indirect bonding tray.

Patients and Methods

Type of the study:

Randomized controlled trial (RCT) where subjects were randomly assorted into experimental and control groups. The effect of treatment was compared between both groups afterwards.

Study setting:

The study was carried out at the Department of Orthodontics, Faculty of Dentistry, Minia University.

Ethical regulations:

- This study was approved by the ethics committee of the Faculty of Dentistry, Minia University.
- A detailed informed consent was signed by the patient or parent if required.

Both the patients and parents had the right to quit the procedure without any commitment either legal or financial.

Study population:

A total of 20 patients (with a total of 200 brackets) who needed fixed orthodontic treatment were included in this study.

Inclusion criteria:

- Patients with complete permanent dentition.
- Patients without previous orthodontic treatment.
- Patients with good oral hygiene.

Patients with intact labial surfaces for all included teeth.

Exclusion criteria:

- Presence of a palatally/lingually blocked-out tooth that will interfere with bracket bonding.
- Patients with hypocalcified teeth.

Method:

- Patients were equally divided into two groups A and B.
    - Group A: Brackets were bonded using an indirect bonding tray made of a transparent flexible silicon [Memosil 2 – Kulzer][1].
    - Group B: Brackets were bonded using an indirect bonding tray made of a double layer of thermoformed sheets.

All upper teeth were bonded (from right second premolar to left second premolar), excluding molar tubes.

Diagnostic records:

1. Medical and dental history.
2. Clinical examination.
3. Photographs.
4. Digital scans.
5. Radiographs:
    - Panoramic.

Lateral cephalometric.

Scanning:

The patient's dentition was transformed digitally into STL file by directly scanning the patient's dentition using [Medit i700][2] intra-oral scanner.

[1] Kulzer, Leipziger Straße 2, 63450 Hanau.

[2] Medit, Songbuk, Kangwon-do, South Korea.

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Figure 1 Intra-oral scanner (a) Medit i700 and (b) Pre-operative scan

Software planning:

The STL file was imported into [Maestro3D software][3]. Teeth were defined by segmenting them from the cast and marking the teeth's mesial and distal contacts. The software then determined the gingival boundaries and outlined the tooth structures. By so, the software could tell the difference between tooth structure and gingiva.

Virtual bracket positioning:

The brackets were chosen from the software library and placed using the software's automatic bracket placement system. The bracket position was assessed from a variety of angles. Then, any necessary changes in brackets positions were done by the operator. Afterwards, the master model with brackets placed was saved in STL format.

[3] Maestro 3D, Via Salvo D'Acquisto, 56025 Pontedera (Pisa), Italia.

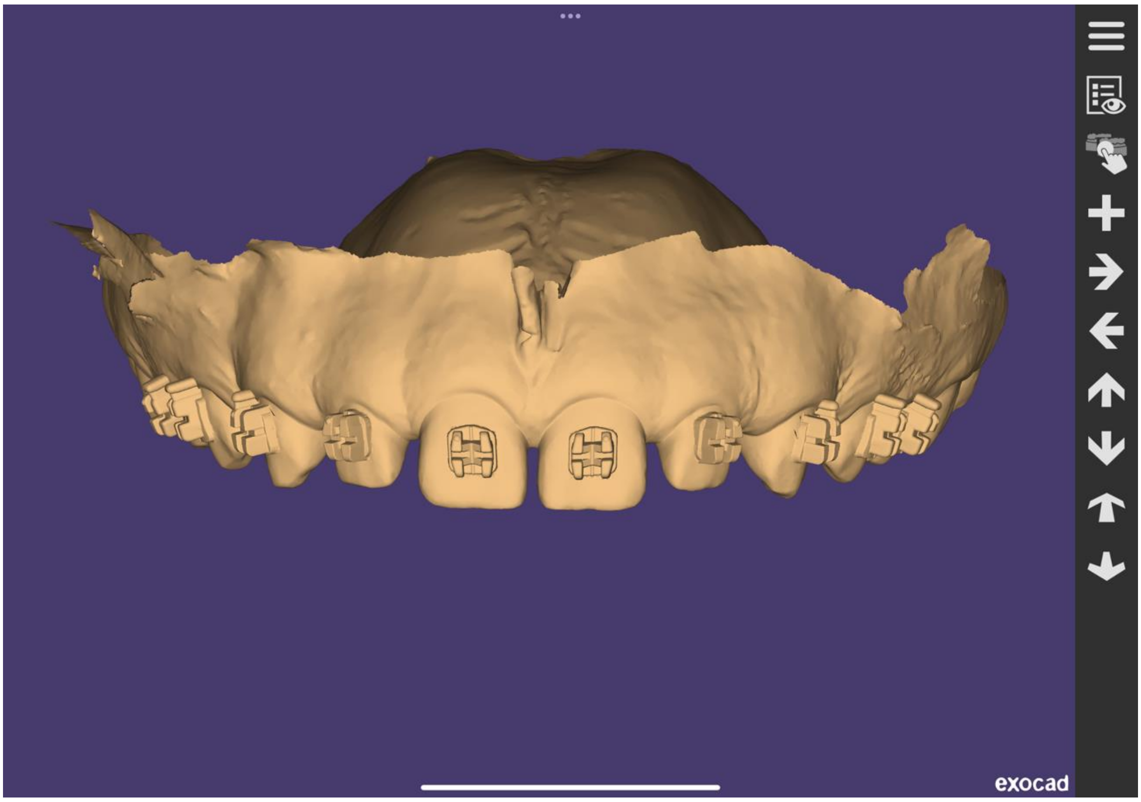

Figure 2 Virtual bracket positioning

Cast 3D printing:

3D printing was then carried out, obtaining an acrylic cast with brackets, properly placed on teeth, without any undercuts.

Figure 3 (a) 3D-printed cast with brackets in place, (b) with blocked-out undercuts

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Contructing the indirect bonding tray:

Group A:

- The tray was made of a transparent flexible silicon [Memosil 2 – Kulzer].

Tray fabrication:

The transparent flexible silicon [Memosil 2 – Kulzer] was injected covering the whole labial/buccal, occlusal, and part of the lingual surfaces of the teeth. The trays were smoothened by putting transparent flat celluloid paper on them before setting to have that smooth finish. After setting, excess material was trimmed off using a scalpel.

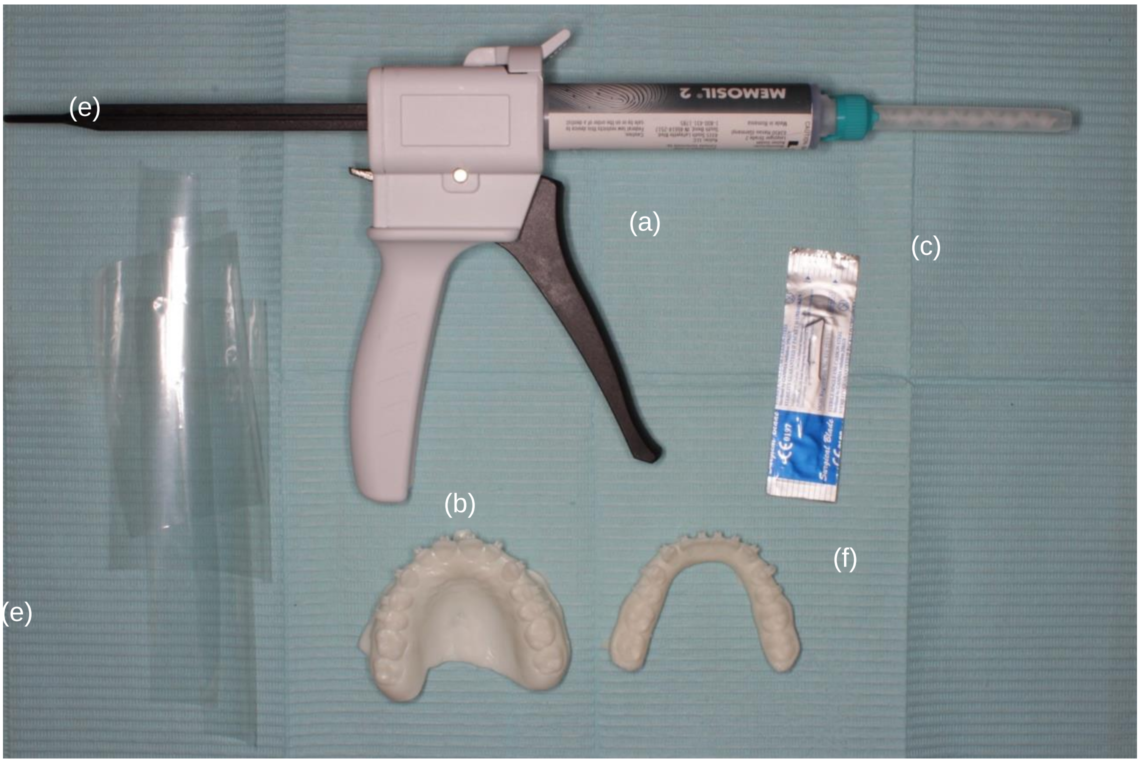

Figure 4 Everything needed for tray fabrication; (a) Memosil 2, (b) dispensing gun, (c) auto-mix tip, (d) casts with brackets on them, (e) celluloid strips, and (f) a scalpel

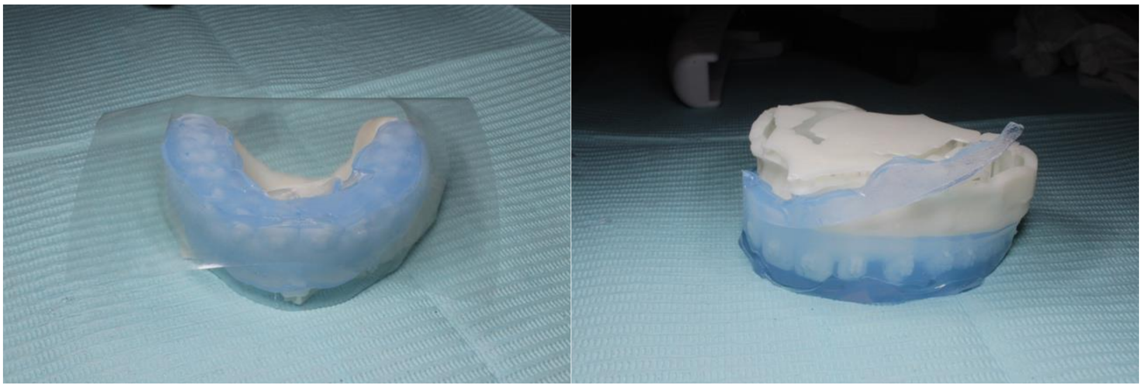

Figure 5 (a) Celluloid strips used to give the tray a smooth finish, and (b) excess was cut off using the scalpel

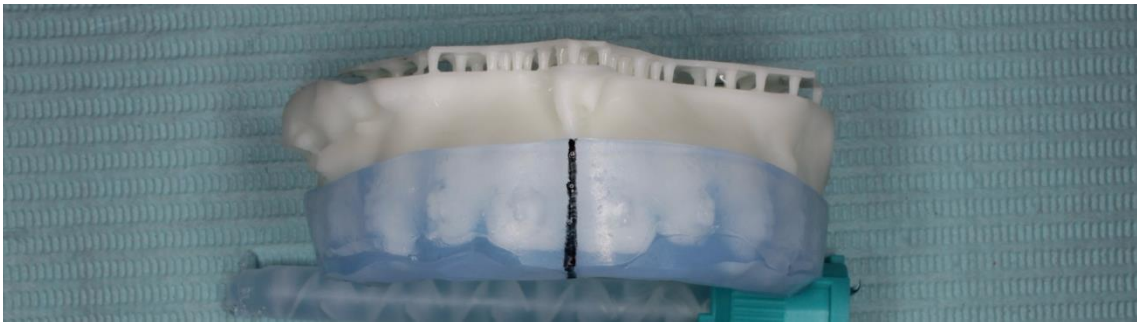

Figure 6 The tray was marked at the midline for easy insertion in patient's mouth

Group B:

- Archived data were used in this group. Eissa, T. A., Rifai, W. M. (2022) [1].
- The tray was made of a double layer of thermoformed sheets.

Tray fabrication:

A double thermoformed transfer tray was constructed over the model. The first layer was a flexible 1 mm sheet and the second layer on top was a rigid 1.5 mm sheet. Then excess was cut off using scissors.

Clinical indirect brackets bonding:

Brackets were placed in the transfer tray. Teeth were isolated, dried, etched, rinsed, and dried again before bond was applied. Composite resin was then applied on the base of each bracket inside the transfer tray. Afterwards, the tray was inserted intra-orally and light-cured while manitaining finger pressure on the tray labially and occlusally. Finally, the transfer tray was gently removed.

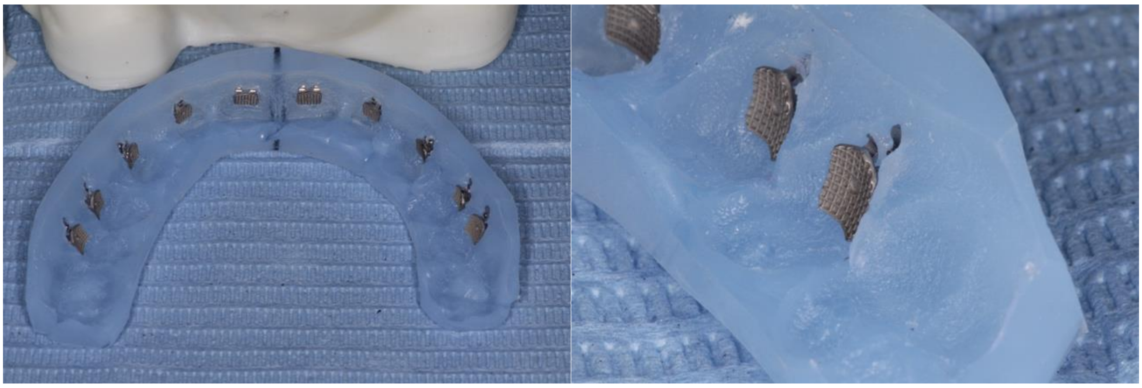

Figure 7 Brackets in their indentations in the transfer tray

Comparing brackets positions:

Models with the virtual bracket placement were called “Pre models”. While real post-bonding scanned models were called “Post models” for easier interpretation. Pre and post models were superimposed and evaluated using [Exocad][4] software. Superimposition was undertaken using teeth surfaces with the local best fit of the software.

[4] Exocad, *Rosa-Parks-Str. 2, 64295 Darmstadt, Germany.*

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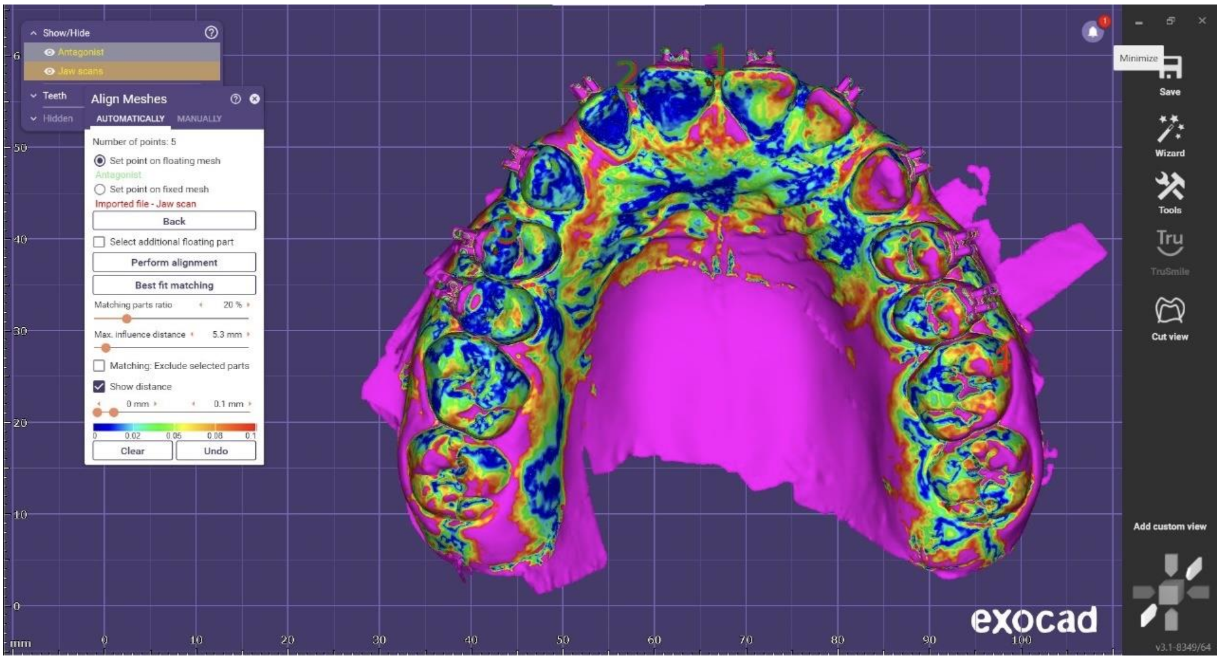

Figure 8 Superimposition of pre and post models using Exocad software

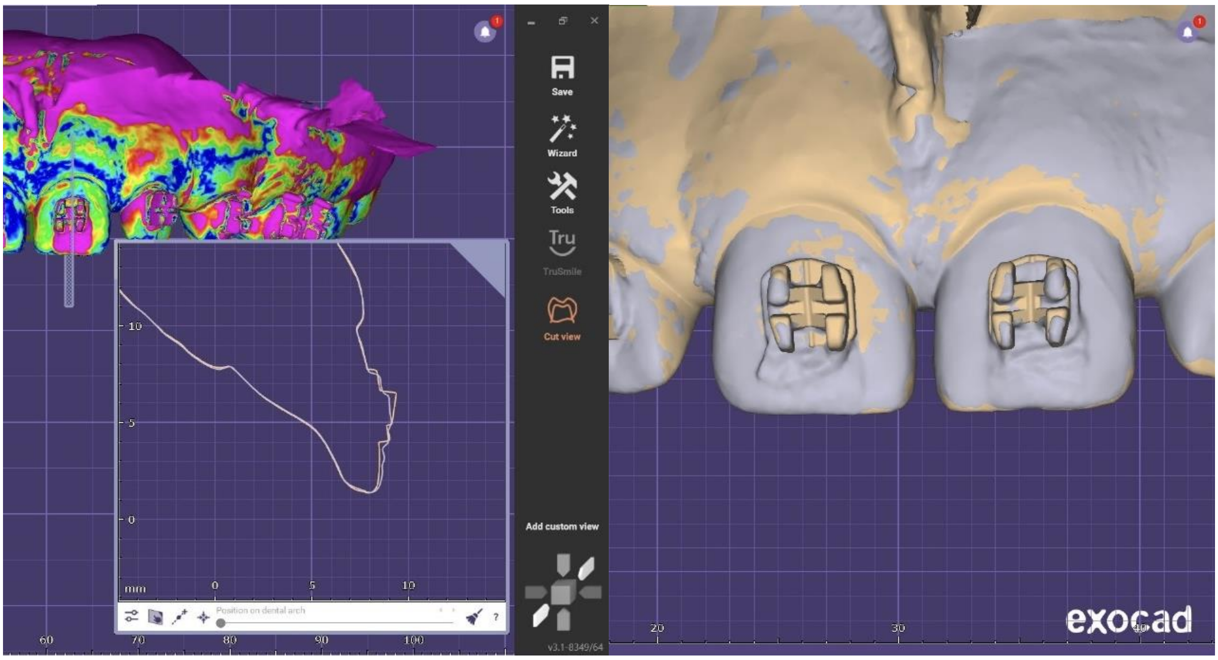

Figure 9 (a) Cut view showing the accuracy of the superimposition and (b) close-up view of superimposed brackets

<u>Bracket deviation measurement:</u>

In vertical measurements (occluso-gingival), a reference point on the tooth was either the incisal edge for incisors or cusp tips for canines and premolars. In horizontal measurements (mesio-distal), a reference point on the tooth was the mesial contact point of the tooth. This reference point was fixed for both pre and post models. The distance was then measured from this reference point to the mid-point of the bracket slot in the pre model and then the same was measured for the post model. The deviation was calculated by subtracting both results.

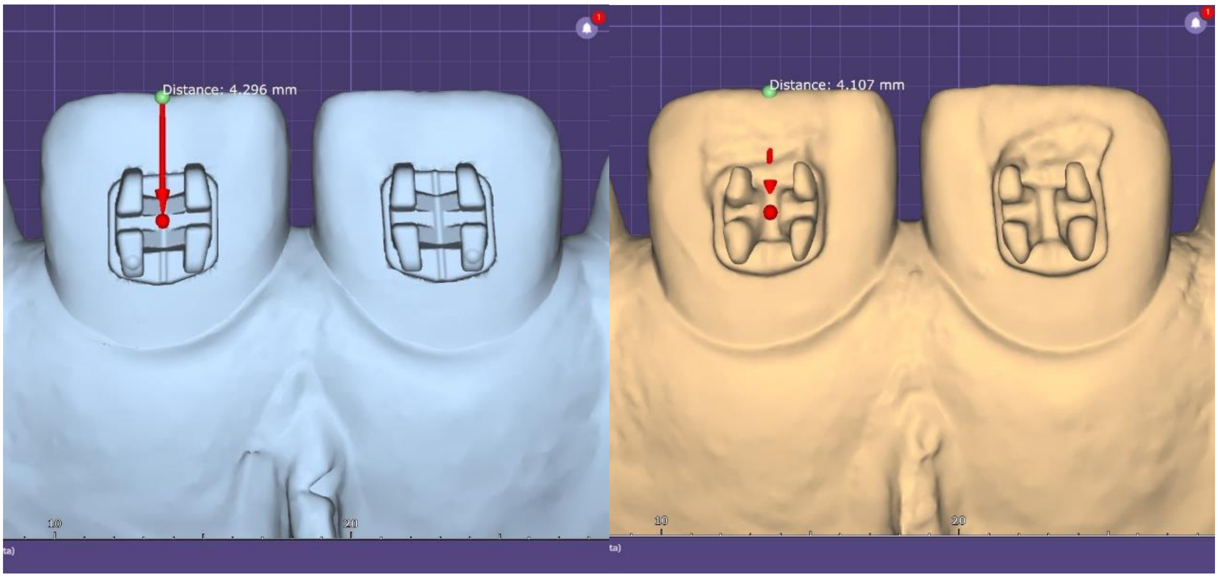

Figure 10 Vertical measurement: (a) Pre model and (b) Post model

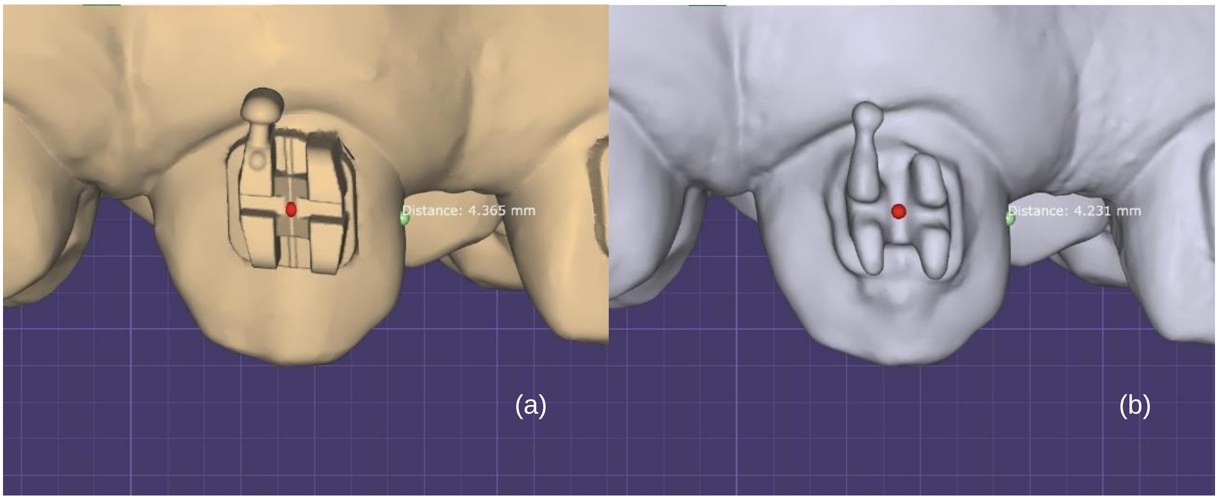

Figure 11 Horizontal measurement: (a) Pre model and (b) Post model

Measurements:

- Mesio-distal direction (X) and occluso-gingival direction (Y).
- In the X axis, + value was distal, – value was mesial.
- In the Y axis, + value was cervical, – value was occlusal.

Data were collected and evaluated for statistical analysis.

Statistical analysis

Data were verified, coded by the researcher, and analyzed using IBM-SPSS 24.0 [IBM-SPSS Inc., Chicago, IL, USA][5]. Descriptive statistics: Means, standard deviations, medians, interquartile ranges

[5] IBM_SPSS. Statistical Package for Social Science. Ver.24. Standard version. Copyright © SPSS Inc., 2012-2016. NY, USA. 2016

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(IQR), frequency, and percentages were calculated.

Analytic statistics:

Chi-square test was used to compare the difference in distribution of frequencies among groups and McNemar for within group comparisons.

Shapiro-Wilk test was used to test the normality of continuous variables.

Student t-test or **Mann Whitney U-test** was carried out to compare the means/medians of dichotomous data as appropriate.

A significant p-value was considered when it is <0.05

Results

Linear occluso-gingival direction (Y-axis) (Vertical) in μm:

(+ means cervical, - means occlusal)

Upper right quadrant

The difference in vertical bracket's deviations (Upper Right) among the studied groups was illustrated in **Table 1 and Fig 12**.

Memosil 2 Group had significantly ($p < 0.001$) higher vertical bracket's deviations (in the occlusal direction [-213 (301)]) than Thermoformed sheets Group (in the cervical direction [131 (59)]) for UR1. Likewise, Memosil 2 Group had significantly ($p < 0.001$) higher vertical bracket's deviations (in the occlusal direction [-172 (81)]) than Thermoformed sheets Group (in the cervical direction [144 (99)]) for UR3. On the other hand, Memosil 2 Group had significantly ($p < 0.001$) lower vertical bracket's deviations (in the occlusal direction [-84 (77)]) than Thermoformed sheets Group (in the cervical direction [483 (209)]) for UR2. Also, Memosil 2 Group had significantly ($p < 0.001$) lower vertical bracket's deviations (in the occlusal direction [-66 (39)]) than Thermoformed sheets Group (in the same occlusal direction [-197 (126)]) for UR4. Unlikely, Memosil 2 Group had insignificantly ($p = 0.127$) lower vertical bracket's deviations (in the occlusal direction [-182 (105)]) than Thermoformed sheets Group (in the same occlusal direction [-201 (157)]) for UR5.

For within group comparison, insignificant difference was observed for the Memosil 2 Group ($p = 0.112$) with all deviated in occlusal direction. Unlikely, for Thermoformed sheets Group, UR4 [-197 (126)] and UR5 [-201 (157)] had significantly ($p < 0.001$) vertical bracket's deviations (in occlusal direction) compared with UR1 [131 (59)], UR2 [483 (209)], and UR3 [144 (99)], in cervical direction.

	Memosil 2 Group (n = 10) (µm)	Thermoformed sheets Group (n = 10) (µm)	P-value
UR1 (n=10)			
• **Mean ± SD**	-194.33 ± 130	123.21 ± 86	**< 0.001***
• **Median (IQR)**	-213 (301)	131 (59)	
UR2 (n=10)			
• **Mean ± SD**	-129.51 ± 189	495 ± 204	**< 0.001***
• **Median (IQR)**	-84 (77)	483 (209)	
UR3 (n=10)			
• **Mean ± SD**	-136.17 ± 120	151.03 ± 61	**< 0.001***
• **Median (IQR)**	-172 (81)	144 (99)	
UR4 (n=10)			
• **Mean ± SD**	-26.83 ± 131	-201.01 ± 134	**< 0.001***
• **Median (IQR)**	-66 (39)	-197 (126)	
UR5 (n=10)			
• **Mean ± SD**	-176.01 ± 189	-204.01 ± 94	= 0.127*
• **Median (IQR)**	-182 (105)	-201 (157)	
P-value**	= 0.112	**< 0.001**	

Table 1 Difference in vertical brackets deviations (UR)

***Mann Whitney U test was used to compare the differences in Median between groups**
****Friedman's Test was used to compare the differences in Median within groups**

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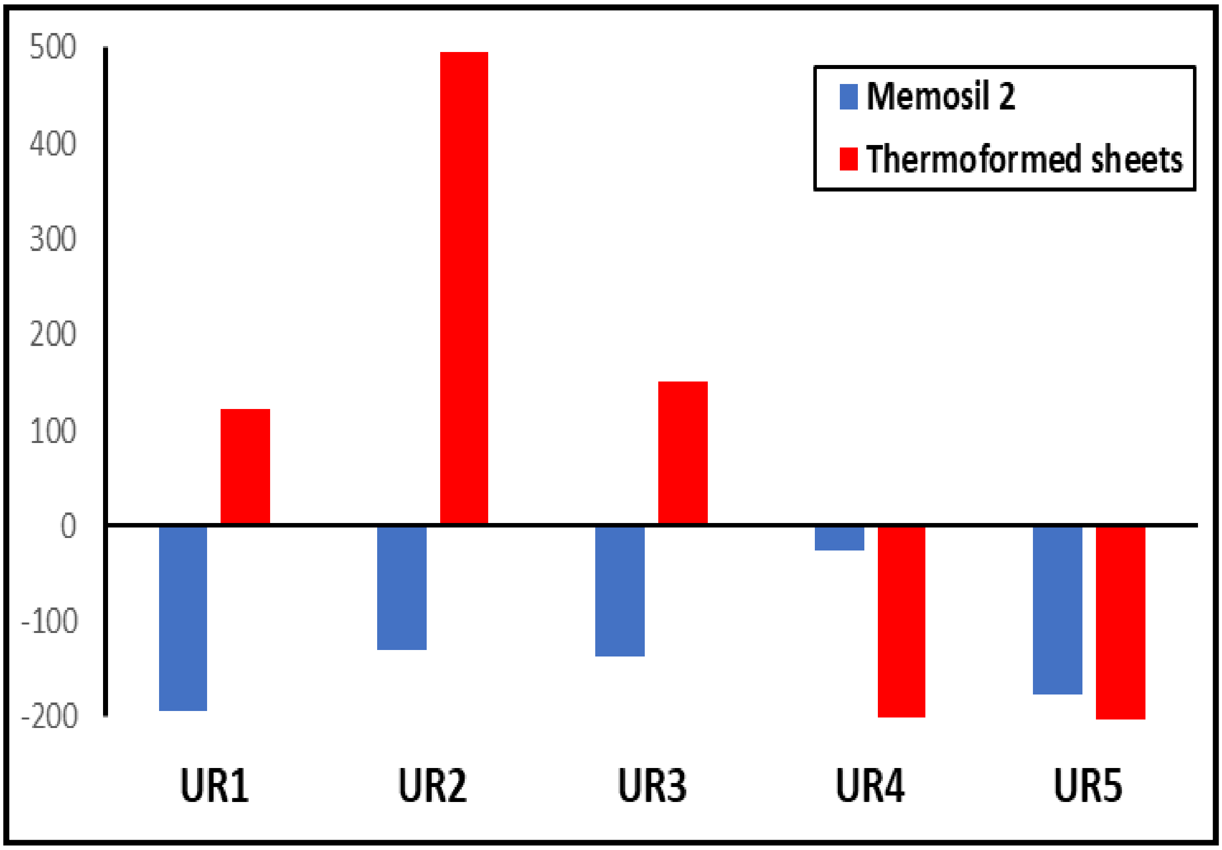

Figure 12 Difference in vertical brackets deviations (UR)

Linear occluso-gingival direction (Y-axis) (Vertical):

(+ means cervical, - means occlusal)

Upper left quadrant

The difference in vertical bracket's deviations (Upper Left) among the studied groups was illustrated in **Table 2 and Fig 13**.

Memosil 2 Group had significantly ($p < 0.001$) higher vertical bracket's deviations (in the occlusal direction [-207 (124)]) than Thermoformed sheets Group (in the cervical direction [81 (92)]) for UL1. Contrarily, Memosil 2 Group had significantly ($p < 0.001$) lower vertical bracket's deviations (in the occlusal direction [-98 (82)]) than Thermoformed sheets Group (in the same occlusal direction [-204 (90)]) for UL3. Likewise, Memosil 2 Group had significantly ($p < 0.021$) lower vertical bracket's deviations (in the cervical direction [103 (93)]) than Thermoformed sheets Group (in the same cervical direction [186 (174)]) for UL4. Unlikely, Memosil 2 had significantly ($p < 0.001$) higher vertical bracket's deviations (in the cervical direction [150 (146)]) than Thermoformed Group (in the occlusal direction [-62 (98)]) for UL5.

For within group comparison, Regarding the Memosil 2 Group, UL4 [103 (93)], UL5 [150 (146)] had significantly ($p < 0.001$) vertical bracket's deviations in cervical direction in comparison with UL1 [-207 (124)], UL2 [-63 (77)] and UL3 [-98 (82)] with vertical bracket's deviations in occlusal direction. Likewise, in the Thermoformed sheets Group, UL1 [81 (92)], UL4 [186 (174)] had significantly ($p < 0.001$) vertical bracket's deviations in cervical direction than UL2 [-101 (188)], UL3 [-204 (90)] and UL5 [-62 (98)] with vertical bracket's deviations in occlusal direction.

	Memosil 2 Group (n = 10) (µm)	Thermoformed sheets Group (n = 10) (µm)	P-value
UL1 (n=10)			
• **Mean ± SD**	-196.50 ± 118.5	75 ± 86	**< 0.001***
• **Median (IQR)**	-207 (124)	81 (92)	
UL2 (n=10)			
• **Mean ± SD**	-126.67 ± 136.1	-117 ± 204	= 0.224*
• **Median (IQR)**	-63 (77)	-101 (188)	
UL3 (n=10)			
• **Mean ± SD**	-58.17 ± 136.2	-199.03 ± 61	**= 0.014***
• **Median (IQR)**	-98 (82)	-204 (90)	
UL4 (n=10)			
• **Mean ± SD**	95.17 ± 176.2	163 ± 134	**= 0.021***
• **Median (IQR)**	103 (93)	186 (174)	
UL5 (n=10)			
• **Mean ± SD**	155.50 ± 120.9	-11 ± 94	**< 0.001***
• **Median (IQR)**	150 (146)	-62 (98)	
P-value**	**< 0.001**	**< 0.001**	

Table 2 Difference in vertical brackets deviations (UL)

***Mann Whitney U test was used to compare the differences in Median between groups**
****Friedman's Test was used to compare the differences in Median within groups**

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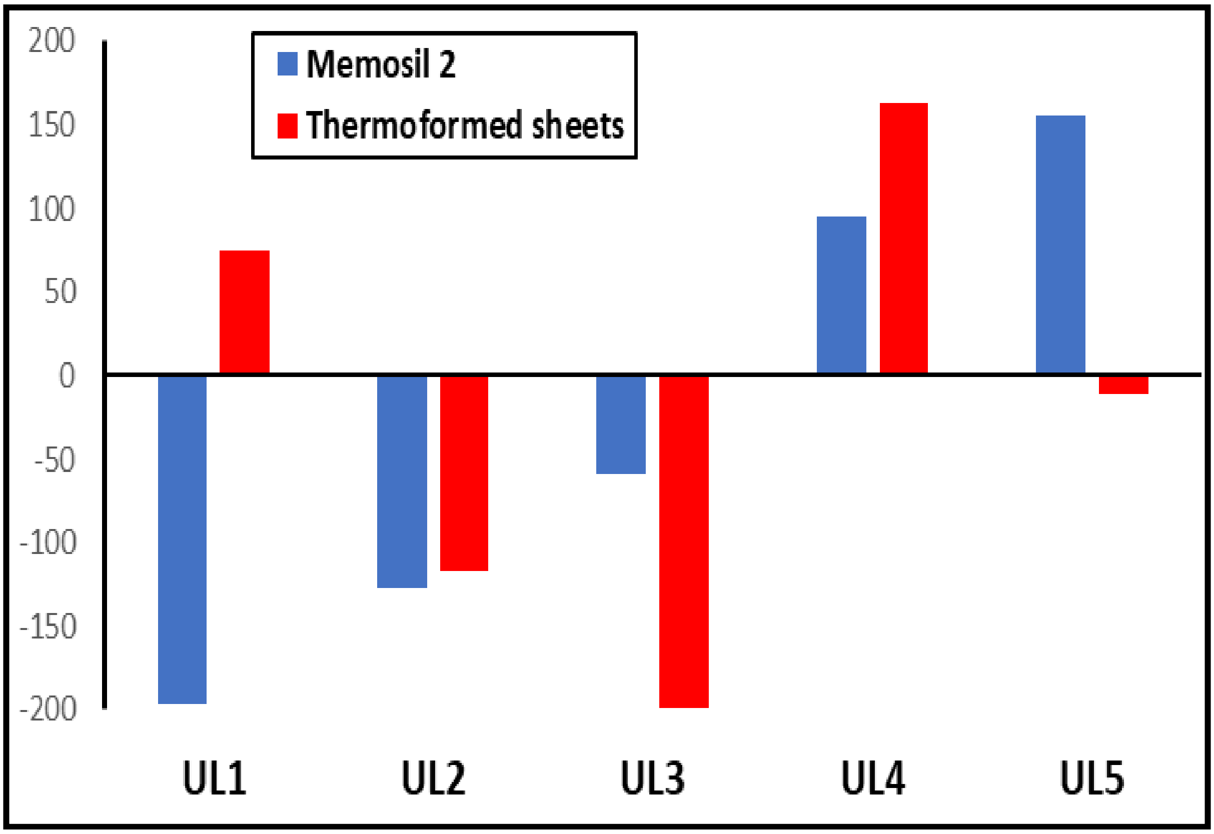

Figure 13 Difference in vertical brackets deviations (UL)

Linear mesio-distal direction (X-axis) (Horizontal):

(+ means distal, - means mesial)

<u>Upper right quadrant</u>

The difference in horizontal bracket's deviations (Upper Right) among the studied groups was illustrated in **Table 3 and Fig 14**.

For UR1 and UR4, Memosil 2 Group had significantly ($p < 0.001$ and $= 0.019$) higher horizontal bracket's deviations (in mesial direction [-134 (89)] and [-139 (148)]) than Thermoformed sheets Group (in distal direction [42 (55)] and in the mesial direction [-22 (93)]). In contrast, Memosil 2 Group had significantly ($p < 0.001$) no horizontal bracket's deviations compared with Thermoformed sheets Group (in the distal direction [167 (188)]) for UR2.

For within group comparison, Regarding the Memosil 2 Group, there were insignificant ($p = 0.066$) horizontal bracket's deviations in mesial direction. On the other hand, in the Thermoformed sheets Group, UR1 [42 (55)] and UR2 [167 (188)] had significantly ($p < 0.001$) horizontal bracket's deviations in distal direction than UR3 [-144 (67)], UR4 [-22 (93)]) and UR5 [-51 (97)] with horizontal bracket's deviations in mesial direction.

	Memosil 2 Group (n = 10) (µm)	Thermoformed sheets Group (n = 10) (µm)	P-value
UR1 (n=10)			
• **Mean ± SD**	-77.50 ± 57.7	37.30 ± 86	**< 0.001***
• **Median (IQR)**	-134 (89)	42 (55)	
UR2 (n=10)			
• **Mean ± SD**	-54.83 ± 112.9	15.6 ± 204	**< 0.001***
• **Median (IQR)**	0 (35)	167 (188)	
UR3 (n=10)			
• **Mean ± SD**	-91.50 ± 28.6	-120.70 ± 61	= 0.442*
• **Median (IQR)**	-101 (28)	-114 (67)	
UR4 (n=10)			
• **Mean ± SD**	-33.50 ± 54.3	-16.70 ± 134	**= 0.019***
• **Median (IQR)**	-139 (148)	-22 (93)	
UR5 (n=10)			
• **Mean ± SD**	-70 ± 85.8	-6.5 ± 94	= 0.228*
• **Median (IQR)**	-31 (84)	-51 (97)	
P-value**	= 0.066	< 0.001	

Table 3 Difference in horizontal brackets deviations (UR)

***Mann Whitney U test was used to compare the differences in Median between groups**
****Friedman's Test was used to compare the differences in Median within groups**

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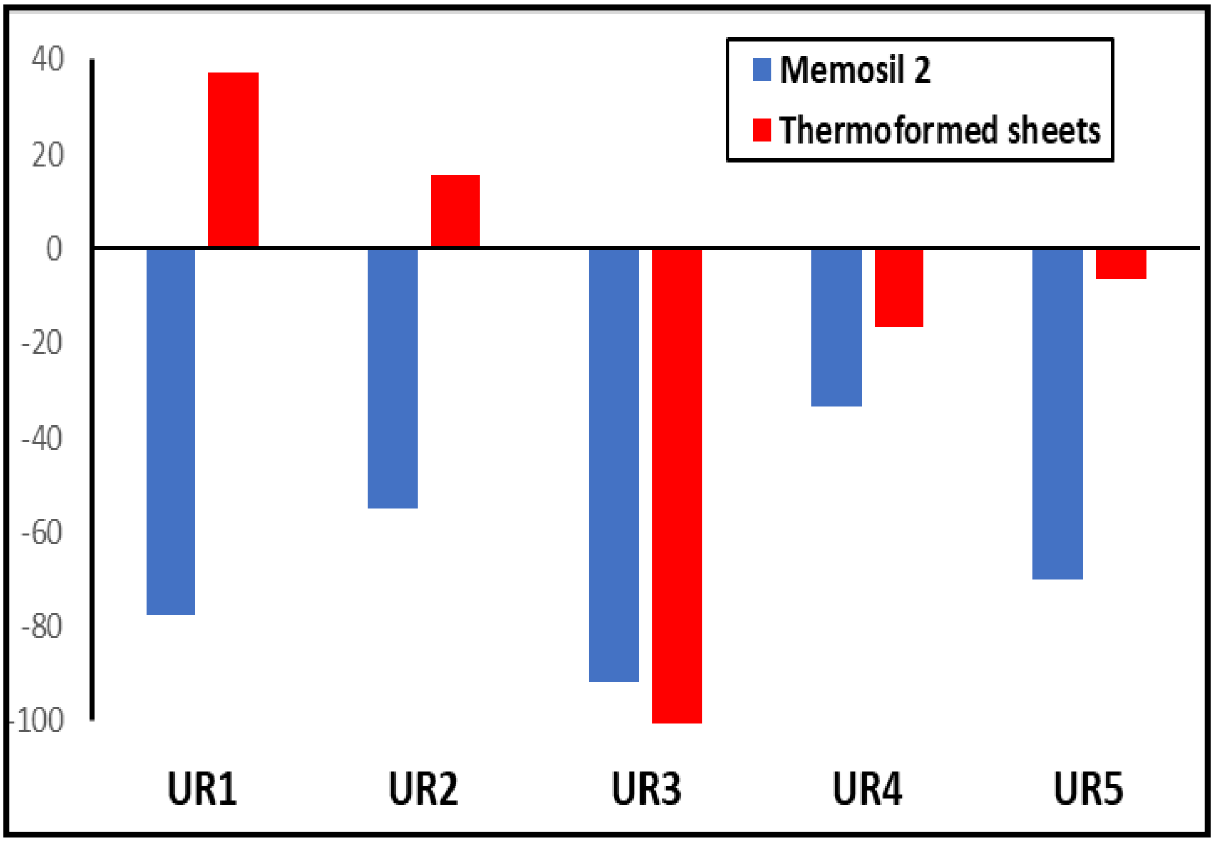

Figure 14 Difference in horizontal brackets deviations (UR)

Linear mesio-distal direction (X-axis) (Horizontal):

(+ means distal, - means mesial)

<u>Upper left quadrant</u>

The difference in horizontal bracket's deviations (Upper Left) among the studied groups was illustrated in **Table 4 and Fig 15**.

The horizontal bracket's deviations were evident in Thermoformed sheets Group for UL1-UL5. In details, Thermoformed sheets Group had significantly ($p < 0.001$) higher horizontal bracket's deviations (UL1: in distal direction [162 (124)] and UL5: [159 (166)]) than Memosil 2 Group (UL1: in mesial direction [-44 (79)] and UL5 with no deviation). For UL2, Thermoformed sheets Group had significantly ($p < 0.001$) higher horizontal bracket's deviations (in mesial direction [-213 (189)] than Memosil 2 Group (in distal direction [25 (61)].

For within group comparison, Regarding the Memosil 2 Group, there were insignificant ($p = 0.054$) horizontal bracket's deviations in mesial/distal/no direction. On the other hand, in the Thermoformed sheets Group, UL1 [162 (124)], UL4 [19 (77)] and UL5 [159 (166)] had significantly ($p < 0.001$) horizontal bracket's deviations in distal direction than UL2 [-213 (189)] and UL3 [-94 (34)] with horizontal bracket's deviations in mesial direction.

	Memosil 2 Group (n = 10) (µm)	Thermoformed sheets Group (n = 10) (µm)	P-value
UL1 (n=10)			
• **Mean ± SD**	-71.67 ± 120.5	137.3 ± 142	**< 0.001***
• **Median (IQR)**	-44 (79)	162 (124)	
UL2 (n=10)			
• **Mean ± SD**	21.5 ± 94.4.1	-171.5 ± 204	**< 0.001***
• **Median (IQR)**	25 (61)	-213 (189)	
UL3 (n=10)			
• **Mean ± SD**	-50.5 ± 33.6	-46.3 ± 61	= 0.646*
• **Median (IQR)**	0 (17)	-94 (34)	
UL4 (n=10)			
• **Mean ± SD**	7.83 ± 131.8	56.1 ± 134	= 0.091*
• **Median (IQR)**	0 (58)	19 (77)	
UL5 (n=10)			
• **Mean ± SD**	-28 ± 116.1	206.9 ± 94	**< 0.001***
• **Median (IQR)**	0 (97)	159 (166)	
P-value	= 0.054	**< 0.001**	

Table 4 Difference in horizontal brackets deviations (UL)

***Mann Whitney U test was used to compare the differences in Median between groups**
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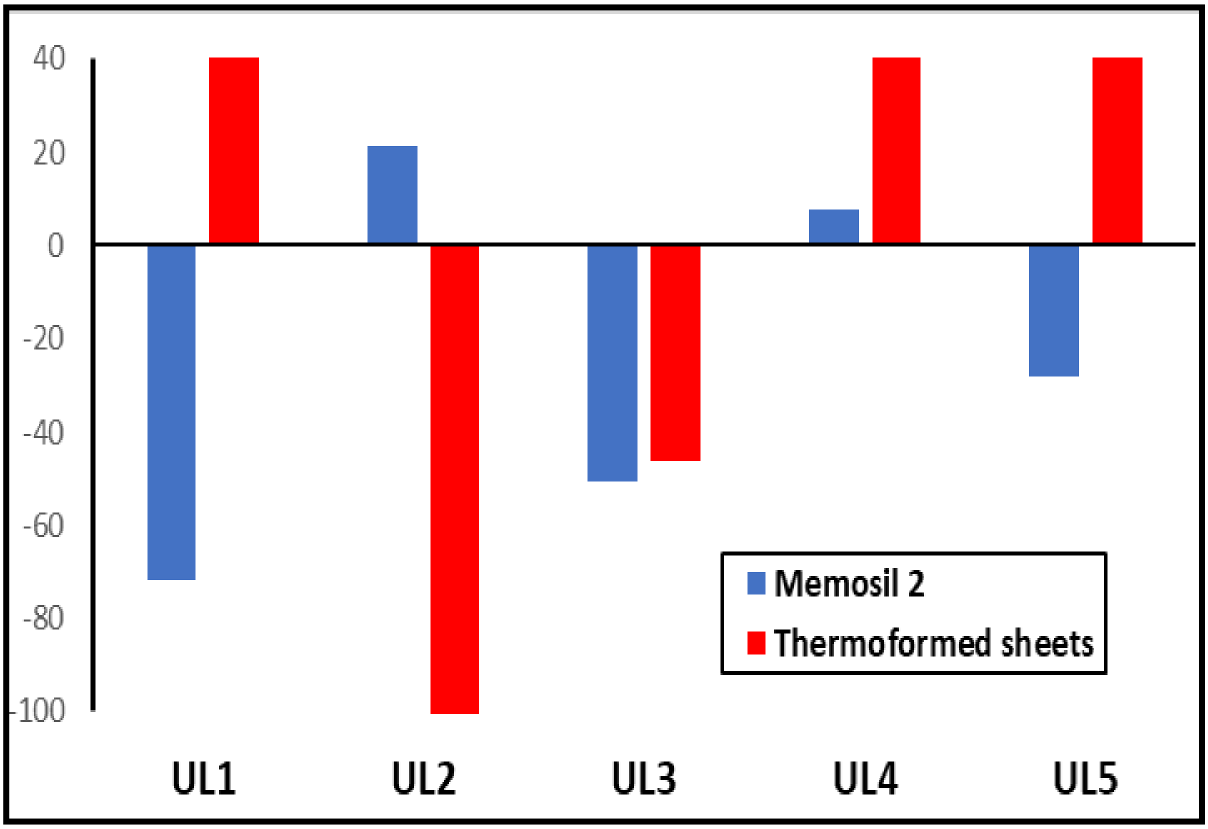

Figure 15 Difference in horizontal brackets deviations (UL)

Discussion

The accuracy of bracket positioning is a crucial factor in the success of orthodontic treatment, as it directly influences the expression of built-in prescriptions and the overall efficiency of fixed mechanotherapy. This study aimed to assess the bracket positioning accuracy using two different materials for the construction of indirect bonding trays: a transparent flexible silicone material (Memosil 2) and a double-layer thermoformed sheet. The results revealed statistically significant differences in vertical and horizontal deviations between the two materials, with implications for clinical practice.

The transparent flexible silicone material (Memosil 2) was chosen to be used in this study because of its ease of fabrication. It required very few things that can easily be available in the dental clinic. Not requiring laboratory work for its fabrication made it easy, simple, and practical for everyday practice in the dental clinic. Its practicality was assumed to encourage orthodontists to embrace indirect bracket bonding in their practices, allowing precise brackets positioning and therefore predictable treatment results and shorter treatment time, avoiding or minimizing the need for brackets repositioning at the end of the treatment.

In the upper right quadrant, Memosil 2 trays showed significantly higher vertical deviations in the occlusal direction for UR1 and UR3 compared to thermoformed trays, which showed cervical deviations. On the other hand, for UR2 and UR4, Memosil 2 trays demonstrated lower vertical deviations. Similar trends were observed in the upper left quadrant, where Memosil 2 trays showed greater occlusal deviations for UL1 but lower deviations for UL3 and UL4. These findings suggest that the material properties of Memosil 2, such as flexibility and elasticity, may contribute to occlusal displacement because of the tray not being fully seated intra-orally, while the rigidity of thermoformed trays may resist such displacement but introduce cervical deviations due to less adaptability to tooth morphology.

These results align with previous studies. For instance, Bachour et al. (2022) [2] stated that 3D-printed rigid trays provided better vertical accuracy, though their study highlighted challenges in torque and tip control. The current study's findings further emphasize the trade-off between material flexibility and precision, suggesting that clinicians should carefully weigh these factors when selecting tray materials. Also, tray manipulation, during insertion in and removal from the patient's mouth, should be careful, taking into consideration the downflows of the material used for tray fabrication.

Horizontal deviations were more pronounced in the thermoformed trays, especially in the upper left quadrant, where distal deviations were significant for UL1 and UL5. On the other hand, Memosil 2 trays showed minimal horizontal deviations, indicating better mesio-distal accuracy. This could be attributed to the silicone material's ability to adapt closely to the tooth surface, reducing the risk of bracket slippage during transfer. Chaudhary et al. (2021) [3] also found that silicone-based trays provided superior transfer accuracy in the mesio-distal direction, supporting the current findings.

However, the thermoformed trays' higher horizontal deviations may arise from their layered construction, which can introduce slight distortions during fabrication. Zhang et al. (2020) [4] noted that double-layer guide plates, similar to the thermoformed trays in this study, exhibited variations in horizontal accuracy depending on thickness, with thinner layers performing better. This emphasizes the importance of tray design and material thickness in achieving accurate bracket placement.

The results of this study corroborate and contrast with several earlier studies. Hodge et al. (2004) [5] found no significant difference in accuracy between direct and indirect bonding techniques, but their study did not account for material-specific differences. In contrast, Nichols et al. (2013) [6] stated that indirect bonding improved reproducibility, particularly with digital workflows, which aligns with the current study's use of virtual bracket positioning. The involvement of digital planning, as seen in this study, likely contributed to the overall accuracy, regardless of tray material.

Karabiber and Eglenen (2024) [7] compared 3D-printed tray designs and found no statistical difference in accuracy between shell and bar designs but showed that shell trays performed better clinically. This parallels the current study's finding that material properties, rather than design alone, play an important role in transfer accuracy. Additionally, Duarte et al. (2020) [8] emphasized the reproducibility of digital workflows, which supports the methodological approach used in this study.

The choice between Memosil 2 and thermoformed trays should consider the specific needs of the clinical scenario and other factors as well. For cases requiring high vertical precision, thermoformed trays may be preferable, while Memosil 2 trays could be

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better suited for minimizing horizontal deviations. Also factors such as time and cost are important. For instance, Memosil 2 trays are easier and quicker to fabricate even in the dental clinic itself, making the overall procedure simple and practical to be applied in everyday practice. While thermoformed trays require a special device for fabrication and sometimes lab work. Regarding the cost, thermoformed trays are much cheaper and more affordable than Memosil 2.

The deviations of both groups showed significant difference statistically, but, if we look closer to the numbers which are in micrometers, all deviations didn't exceed 0.5 mm in either direction. This was considered clinically acceptable as per the ABO recommendations [9].

Moreover, the study emphasizes the advantages of digital workflows in orthodontics. Virtual bracket positioning and 3D-printed models, as employed here, reduce human errors and enhance reproducibility. Balut et al. (2020) [10] advocated for digital planning in indirect bonding, citing efficiency and accuracy gains, which comply with the current results.

This study has limitations, including measurements in occluso-gingival and mesio-distal directions only and focus on upper arch bonding. Future research should evaluate in/out direction and angular measurements and include mandibular teeth to provide a comprehensive assessment. Additionally, long-term clinical outcomes, such as bond failure rates and treatment efficiency, need investigation.

Another limitation in this study is the use of Memosil 2 alone in fabrication of the tray. Memosil 2 is flexible and flowy before curing but there are other transparent silicone materials, which are more flowy and flexible but less firm and stiff after curing, that can be used as buttons covering each bracket on the dental cast before application of Memosil 2, to help adapt the tray more precisely around each bracket. Not using these materials lead to some clinical difficulties; brackets falling out of place in the tray during tray insertion in the patient's mouth. Future studies should include these more flowy materials with Memosil 2 for tray fabrication for easier and more practical clinical use.

Emerging technologies, such as AI-driven bracket positioning and advanced 3D printed trays, could further refine indirect bonding accuracy. Studies like those by Park et al. (2021) [11] and Martin et al. (2015) [12] highlight the rapid evolution of orthodontic tools, suggesting that ongoing innovation will continue to improve precision.

Recent advances in digital orthodontics, such as AI-assisted bracket positioning [13], bioactive adhesives [14], and 3D printed transfer trays, offer promising avenues for improving indirect bonding accuracy. For instance, AI algorithms can predict optimal bracket positions based on tooth morphology and treatment goals, reducing manual errors [15]. Bioactive adhesives, which enhance bond strength and reduce flash, could complement the materials tested in this study [16].

Furthermore, the role of intraoral scanners in indirect bonding has expanded, with newer versions offering higher resolution and faster processing times [17]. These developments align with the digital workflow used in this study and could further streamline the process. The inclusion of CBCT data for root-based bracket positioning, as explored by

Taneva et al. (2015) [18], represents another frontier for improving accuracy.

This study demonstrates that both Memosil 2 and thermoformed trays offer distinct advantages and limitations in bracket positioning transfer accuracy. The choice of tray material should be guided by the specific clinical requirements and the desired balance between vertical and horizontal precision. Digital workflows, as employed here, enhance reproducibility and reduce human errors, supporting their growing adoption in orthodontics. Future research should explore 3D printed trays and advanced technologies to further optimize indirect bonding outcomes.

Conclusion

This study assessed the accuracy of bracket positioning using two indirect bonding tray materials: transparent flexible silicone (Memosil 2) and double-layer thermoformed sheets. While thermoformed trays provided better vertical transfer accuracy, Memosil 2 trays excelled in minimizing horizontal deviations. Clinicians should consider these trade-offs when selecting tray materials for indirect bracket bonding.

Future research should explore 3D printed trays and advanced technologies, such as AI bracket positioning, to further enhance accuracy. Additionally, long-term clinical outcomes will provide deeper thoughts into the practical implications of these findings. Overall, this study emphasizes the potential of digital orthodontics in improving treatment precision and efficiency.

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