Does Impression Material Thickness Impact the Accuracy of Addition Silicone Impressions and the Resultant Casts? A 3D Analysis

Keywords

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ABSTRACT

Objectives: Conflicting evidence exists regarding the optimal impression thickness and the influence of tray spacing on the accuracy of elastomeric impressions and resulting casts. This study evaluated the effect of three tray spacings (2 mm, 4 mm, and 6 mm) on the dimensional accuracy of three addition silicone impression materials (Aquasil, Panasil, and Elite-HD). Methods: Forty-five impressions of a partially dentate maxillary resin cast were made using standardized custom trays with designated spacer thicknesses. Impressions were scanned using a desktop scanner, and casts were poured into type IV dental stone and subsequently scanned. A digital reference cast was generated and used to superimpose all test scans. Deviations were measured across the full arch, palate, and dentulous-edentulous (horseshoe) regions using digital metrology software. Data were analyzed using multiple regression and Tukey HSD post-hoc tests ($\alpha = 0.05$). Results: Spacer thickness and material significantly influenced impression and cast accuracy, with higher deviations observed in the horseshoe region compared to the palate ($p < 0.001$). Conclusions: Panasil at 6-mm spacing produced the most accurate impressions across all regions. Clinical relevance:For cast accuracy, Elite-HD at 4-mm spacing showed the lowest deviation in the palate, while Panasil at 2-mm spacing demonstrated superior accuracy in both full arch and horseshoe regions.

INTRODUCTION

Making an impression is a crucial step in the construction of a fixed or removable dental prosthesis.[1] To provide an accurate prosthesis fit, it is essential to accurately capture the tissue surface throughout the impression making procedures.[2] Rudd and coworkers[3] summarized several potential causes of ill-fitting removable partial denture frameworks, many of which arise from technical errors during the impression-making process. These include improper tray selection, inadequate spacer design, poor material handling, insufficient setting time, and premature removal of the impression.[3] Such procedural inaccuracies can lead to distortion of the impression and subsequent inaccuracy in the resultant stone cast.[3] The greatest vertical distortion has been observed in the palatal region of poured casts, with deviations up to 302 μm documented.[4] Therefore, the accuracy of a removable prosthesis is critically dependent on the accuracy of both the impression and the resulting cast.

A variety of materials can be used to produce impressions for either fixed or removable prosthetic devices.[5,6] Several reports have indicated that addition silicone exhibits superior dimensional stability compared to hydrocolloids as well as other elastomeric impression materials, particularly polyether and polysulfides.[7-10] A variety of addition silicone viscosities are available, including light body, monophase (medium body), heavy body, and putty consistency.[11] Monophasic polyvinylsiloxane (PVS) impression materials are particularly formulated for creating accurate impressions in a single step.[12,13] Custom trays, typically fabricated from auto-polymerizing or light-cured resins, are recommended for elastomeric impressions to ensure uniform material thickness and minimize dimensional distortion during setting.[8-10,14] These traditional methods are cost-effective and accessible, but they may be subject to polymerization shrinkage, human error in adaptation, and variability in tray thickness. In contrast, additive manufacturing technologies such as 3D printing allow for digital design and precise reproduction of tray geometry, offering greater standardization, reproducibility, and workflow integration.[15,16] However, 3D printing requires specialized equipment, may involve longer production times depending on the printing method, and raises concerns regarding the mechanical properties and biocompatibility of certain printable resins.

To date, the dimensional accuracy of elastomeric impression materials as well as stone casts has been examined.[8,17-22] Dimensional accuracy is characterized by replication of fine details in the impression. It is recommended by the American Dental Association (ADA) No.19 specification that elastomeric impression materials reproduce details of 20 µm for all viscosities except those with very high viscosities, which should reproduce details of 75 µm.[23] Several factors could impact the accuracy of silicone impression materials, including chemical formulations, filler content, polymerization shrinkage, heat changes, moisture contamination, setting reactions, hardness, time, by product release, hydrophilicity, storage time, impression type, impression technique, impression gap thickness, and force during impression removal.[24-33]

The most common methods for evaluating impression accuracy have historically relied on indirect linear measurements of poured stone casts, such as arch width or inter-abutment distances, using calipers, dial gauges, or non-contact optical microscopes.[34-38] These conventional techniques cannot isolate errors inherent to the impression material and are limited in their ability to capture spatial or volumetric distortion. Additionally, they often require physical sectioning and restrict analysis to a few localized landmarks or linear segments.[36,39-41] In contrast, recent advancements in digital metrology have enabled the use of 3D surface analysis combined with best-fit superimposition algorithms. This approach allows for the comparison of thousands of coordinate points across the entire region of interest, offering high-resolution, three-dimensional deviation mapping.[20,22,42,43] It provides a more comprehensive, non-destructive, and reproducible method for evaluating the dimensional accuracy of both impressions and casts, and facilitates the visualization and quantification of distortion across complex anatomical surfaces.

The literature presents a few contradictory findings regarding tray spacers and elastomeric impression materials in achieving accurate prosthesis fabrication. There is disagreement over what should be the ideal thickness of the impression within the tray.[8,21,38] The most accurate impression would require a 2-4 mm spaced tray to make an accurate cast according to some researchers.[8,21] In contrast, others found that a space of 2-6 millimeters did not affect the impression accuracy.[29] Therefore, this study aimed to investigate the impact of three impression gaps on the dimensional accuracy of three different addition silicone impression materials and their resultant casts using a 3D surface analysis software program. According to the first null hypothesis, impression gap thickness has no effect on the dimensional accuracy of the three tested impression materials, their resultant casts and that all evaluation areas are equally accurate. The second hypothesis states that all tested impression brands are similar in their accuracy in each of the areas evaluated.

MATERIALS AND METHODS

CUSTOM TRAY DESIGN AND PREPARATION

Partially dentate maxillary resin cast (Kennedy class II modification 1) was scanned using a laboratory scanner (E4, 3Shape A/S, Copenhagen, Denmark) outputting the reference data, which was labelled as digital reference cast (DRC). Previous researchers validated the accuracy of this scanner (3.5 ± 0.7 µm) for generating reference data.[44,45] The DRC was then imported to custom tray design software program (Zirkonzahn.Tray, Zirkonzahn, South Tyrol, Italy) to design three perforated custom trays using three different impression gaps; 2 mm, 4 mm, and 6 mm. Perforated trays were used to allow passive escape of excess impression material during seating, minimizing hydraulic pressure and promoting complete tray adaptation to the cast surface. The perforations also provided mechanical retention between the set impression and the tray during removal. For a uniform and standardized thickness of the impression, three tissue stoppers were designed, and the overall border was designed to touch the cast at close contact *(Figure 1)*. The tray design file was imported into a stereolithography-based 3D printer (Form 2, Formlabs, Somerville, MA, USA) to fabricate 45 custom trays (n = 5 per subgroup) using a dedicated custom tray resin (Custom Tray Resin, Formlabs, Somerville, MA, USA). Printing was performed in a horizontal orientation with a 200 µm layer thickness. Post-processing included washing in ≥99% isopropyl alcohol (10 minutes, Form Wash, Formlabs, Somerville, MA, USA), air drying (30 minutes), and post-curing at 60 °C for 30 minutes (Form Cure, Formlabs, Somerville, MA, USA), following manufacturer guidelines.

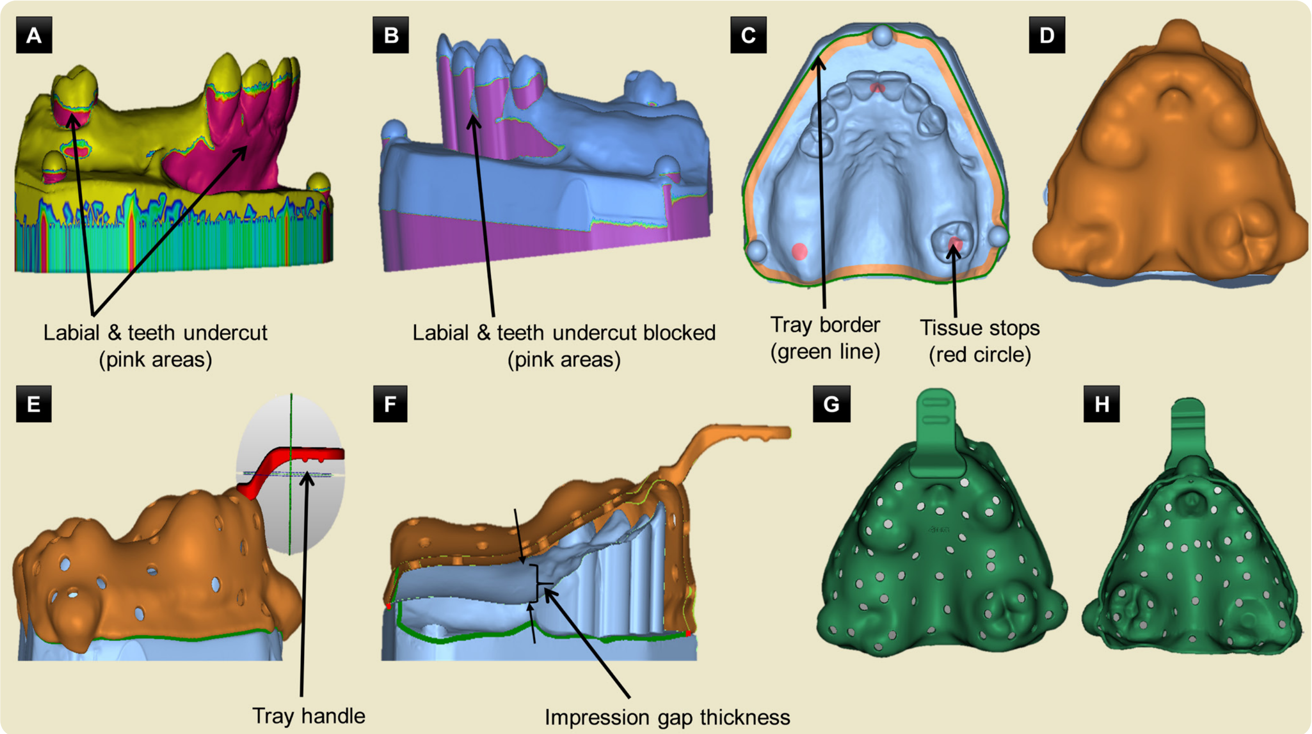

Figure 1: Steps of customized tray design using Zirkonzahn software. (A) Automatic surveying. (B) Automatic block-out of undesirable undercuts. (C) Drawing the custom tray outline and the three tissue stoppers as indicated by the three red circles. (D) Building up the drawn design. (E) Addition of the tray handle and adjustment. (F) Cross-sectional view to detect the impression gap and the small red dots representing close contact at margins of tray. (G) Top view of the final custom tray. (H) Impression surface of the final designed tray.

SAMPLE SIZE

Three hydrophilic addition silicone impressions (Aquasil Ultra+ Medium Regular Set, Dentsply Sirona, USA), (Panasil monophase Medium, Kettenbach Dental, Germany), and (Elite HD+ Monophase Medium Body, Zhermack, Germany) were used. All materials were addition-cured, medium-viscosity, and monophasic, with manufacturer-reported hydrophilic properties. This standardized selection minimized variability related to viscosity, setting chemistry, or application protocol, allowing for controlled comparisons of impression accuracy across different tray spacing conditions. Table 1 presents a comparative overview of the chemical composition of the three materials, based on publicly available safety data sheets

Table 1. Chemical composition of the three monophase addition silicone impression materials evaluated.

Component	Aquasil Ultra+	Panasil Monophase	Elite HD+ Monophase
Vinyl-terminated polydimethylsiloxane	Present	Present	Present
Hydrogen-terminated polysiloxane	Present	Present	Present
Crystalline silica (quartz/cristobalite)	<30% (quartz)	5-10% cristobalite, 3-5% quartz	5-8% cristobalite, 3-5% quartz
Amorphous silica (precipitated/fumed)	<30% total (includes fumed)	10-25%	4-7%
Pyrogenic silica (Colloidal/ nanoform)	0.5-2%	Not specified	0.5-2.5%
Titanium dioxide (CI 77891, whitening agent)	<10%	Present	Present
Ethoxylated surfactants (non-ionic)	Present	Proprietary	0.3-0.5%
Pigments and colorants (e.g., iron oxides)	Present	Present	Present
Ultramarine/red pigments	Present	Not specified	Not specified
Platinum catalyst (addition-cure mechanism)	Present	Present (in ppm)	Present (in ppm)
Fragrance	Trace (peppermint oil)	Not present	Not present

and manufacturer specifications. Figure 2 summarizes the main workflow followed in this investigation. A priori power test was conducted with a program (G*power 3.1.9.7, Heinrich-Heine-Universität Düsseldorf, Germany), and the analysis revealed that a minimum sample size of four was required (power: 0.95, effect size: 0.321). Hence, the study was powered by using five samples for each subgroup.

IMPRESSION PROCEDURE

All custom trays were coated with a thin, uniform layer of tray adhesive (3M VPS Tray Adhesive Refill, 3M, USA) and allowed to dry. Impression material was dispensed into each tray using a mixing gun (3M Garant Dispenser, 3M, USA). The tray was then seated onto the cast by a single operator (E.N.) using standardized finger pressure. Operator calibration was performed in a pilot phase to ensure consistent seating force, guided by visual confirmation of complete contact between the tray borders and the cast surface. This ensured uniform impression material thickness across all samples (*Figure 3*). This pressure was maintained for 10 minutes to allow for complete polymerization. A minimum of double the suggested setting time in oral cavity was allowed for all impressions to set on the cast to account for polymerization happening at ambient temperature (˜ 25°C) instead of the oral temperature (˜ 32°C).[23] After polymerization, all impressions were visually inspected. Any impressions exhibiting air bubbles, voids, distortions, or inhomogeneities were excluded. A total of 45 impressions (n=15 per material) were completed across the three materials. To ensure standardization and reproducibility, all impressions were made by the same investigator (E.N)

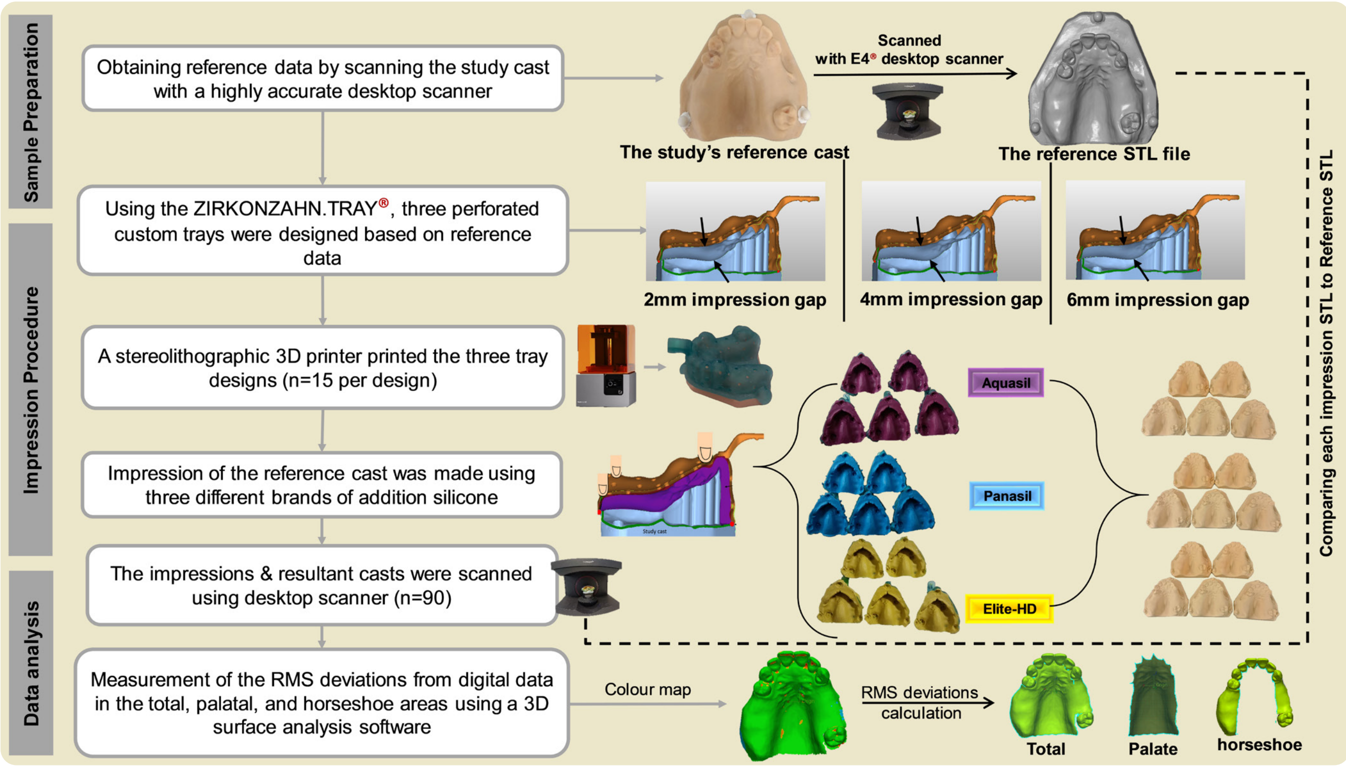

Figure 2: Main study workflow.

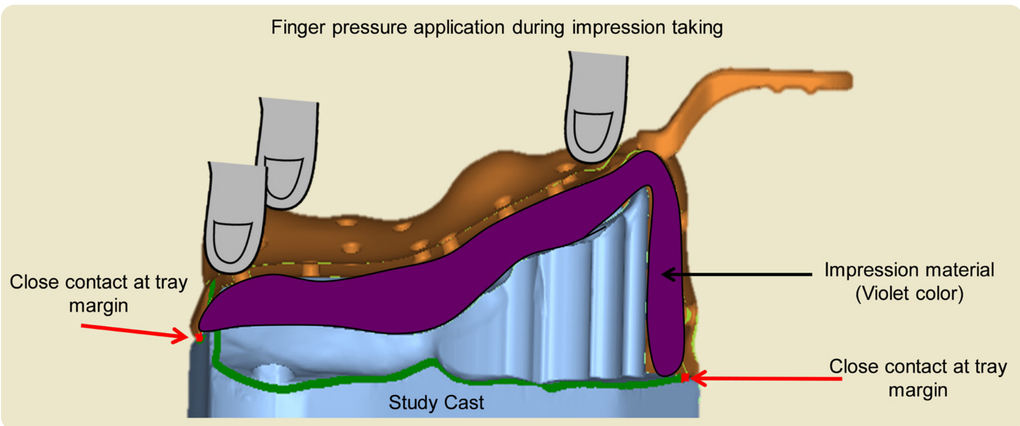

Figure 3: Illustration of the customized tray from a cross-sectional perspective, simulating the impression taking procedure by applying finger pressure. There is close contact at the tray margins, as indicated by small red dots (pointed by red arrows).

on the same day and in the same controlled environment. Impressions were stored in sealable plastic bags at room temperature (20-23°C), in accordance with manufacturer guidelines, until digitization.

IMPRESSION SCANNING AND GYPSUM CAST PRODUCTION

After 24 hours, each impression was scanned with a desktop scanner (E4, 3Shape A/S, Copenhagen, Denmark). After scanning all impressions, type IV dental stone (GC Fujirock EP Classic, GC Europe, Belgium) was utilized for pouring all impressions. Surfactant (Surfactant, Harvest Dental, UK) was sprayed onto the impressions' surface before pouring.[46] A ratio of 10 mL water to 100 g of powder was utilized to mix the stone using an automatic vacuum mixing machine (Smartmix X2, Amann-Girrbach, Austria) and all mixes were vibrated (Miniexport, Dentalfarm, Italy) and poured, then left to set (30-40 minutes) according to the manufacturer's instructions. One hour later, the stone casts were separated and labelled with numbers for each cast group. Subsequently, the stone casts were scanned with the same desktop scanner used to scan impressions.

THREE-DIMENSIONAL ANALYSIS

All scanned impressions and casts were imported into the digital metrology software (Geomagic Control X, version 2022, 3D Systems, USA) for surface deviation analysis. Each test scan was first aligned with the digital reference cast (DRC) using automatic global registration, followed by local best-fit alignment. Importantly, the entire surface of the model was used as the region of interest (ROI) for alignment, rather than selecting specific anatomical landmarks. This strategy was adopted to ensure consistency and to avoid potential bias, as no single area could be assumed to remain dimensionally stable throughout the impression and cast fabrication process.[44]

Root mean square (RMS) deviations were calculated for three predefined regions of interest: the total area (entire arch), the palatal region, and the dentulous-edentulous (horseshoe) region. A standardized digital template was used across all comparisons to ensure consistency in zone selection. For visualization, color-coded deviation maps were generated with a set scale of ±0.3 mm and no tolerance band. In these maps, green represented minimal deviation from the DRC, blue indicated negative deviation (inward displacement), and red to yellow signified positive deviation (outward displacement), as illustrated in Figure 2.

STATISTICAL ANALYSIS

Data were analyzed with a statistical program (JMP, Version 17 Pro, SAS Institute Inc., Cary, NC, USA). Shapiro Wilk normality tests revealed that each measurement group's distributions were normally distributed ($p > 0.05$). Hence, full factorial multi regression analysis with Tukey HSD test was used to determine if the gap thickness affected the 3D measurements in the total area, palatal area, and in the horseshoe area, and whether different brands were more accurate than the others ($\alpha = 0.05$).

RESULTS

QUALITATIVE ANALYSIS (COLOR MAPS)

The gap thickness, impression material, evaluated area, and the interaction between these factors significantly influenced the accuracy of the impressions and resulting casts ($p < 0.001$). Color map for impression accuracy showed that 6 mm Panasil had the most uniform distribution of color maps among all impressions and gap thicknesses. Those for resultant casts showed that 4 mm thickness in both Elite-HD and Aquasil had more uniform color maps (*Figures 4-6*). The color maps also indicated that more deviations (positive or negative) were observed in the horseshoe area, which was also in agreement with the RMS deviations. In all impression materials and among all gap thicknesses, the horseshoe area showed significantly higher deviations ($p < 0.001$) in comparison with the palatal area based on the letters from the *post hoc* analysis *(Table 2*). Nevertheless, certain brands and thicknesses of impressions were more prone to these deviations than others. For instance, among all the materials, the 2 mm Elite-HD had the highest horseshoe deviations (71.9 ± 6.5 μm), which was significantly different ($p < 0.001$) from all other gap thicknesses and brands. In addition to this, both Aquasil and Elite-HD had more horseshoe deviations than Panasil *(Figures 4-6*).

IMPRESSION ACCURACY

For impression accuracy, 6 mm Panasil had the lowest RMS deviations in all the areas evaluated: total (28.5 ± 7.2 μm), palate (14.7 ± 3.3 μm), and horseshoe area (40.8 ± 4.2 μm). However, no significant difference was found between all gap thicknesses *(Table 2*). Among other gap thicknesses within Aquasil, the 4 mm gap had the lowest palatal (18.1 ± 5.9 μm), and horseshoe (57.5 ± 4.3 μm) deviations. However, no significant difference was observed between all gap thicknesses in all evaluated areas. Within the Elite-HD group, the 4 mm gap recorded the lowest deviation ($p < 0.05$) among all other gap thickness in all areas evaluated (total: 32.8 ± 5.1 μm, palate: 19.9 ± 5.6 μm, horseshoe area: 53.9 ± 6.5 μm) *(Table 2, Figures 4, 5, and 6A*).

RESULTANT CASTS ACCURACY

For resultant cast accuracy, the 4 mm Elite-HD had the lowest palatal deviations (20.5 ± 6.6 μm, $p < 0.05$) among all groups and gap thicknesses, followed by the 4 mm Aquasil (21.3 ± 4.1 μm), and 2 mm Panasil (21.4 ± 6.5 μm). While 2 mm Panasil had the lowest horseshoe deviations (30.6 ± 5.4 μm, $p < 0.05$) among other tested groups and gaps. The horseshoe deviations were significantly higher than palatal deviations in all brands and gap thicknesses except for Elite-HD's 4 mm gap thickness *(Figure 6B, Table 3*). Aquasil casts recorded the highest palatal and total accuracy with a gap thickness of 4 mm compared to other gap thicknesses within the same brand. While the 6 mm gap in Aquasil had the highest horseshoe accuracy (40.6 ± 6.1 μm, $p < 0.05$) among other gap thicknesses in the same brand. With respect to Panasil, it had the highest accuracy in all areas evaluated with a 2 mm thickness. Nevertheless, it was significantly different from other gap thicknesses within the same brand, while it was not significantly different from the 2 mm gap in total area. Within Elite-HD, the 4 mm gap obtained the highest accuracy ($p < 0.05$) in all areas evaluated among other gap thicknesses (*Figure 6B*, *Table 3*).

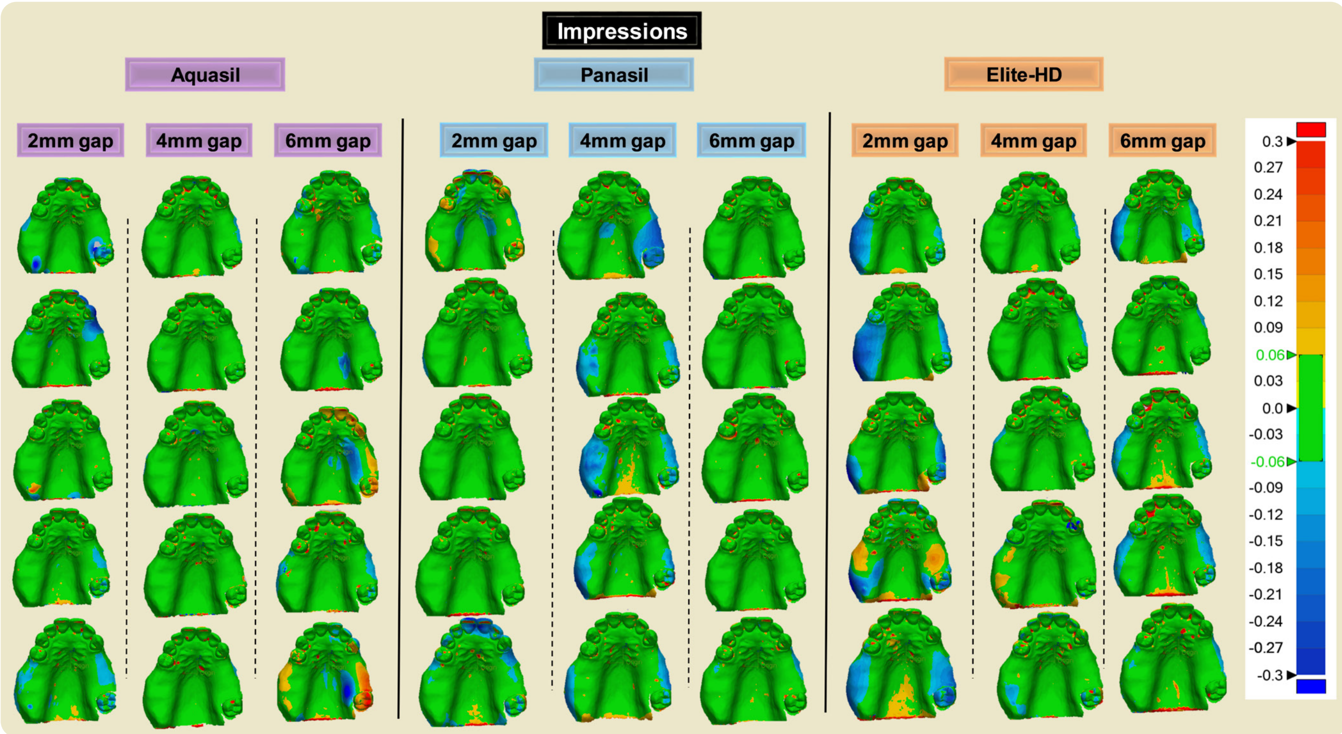

Figure 4: Color map analysis of the three addition silicone impressions (Aquasil, Panasil, Elite-HD) with three gap thicknesses; 2 mm, 4 mm, and 6 mm. Color map scale was adjusted to 300 μm in negative and positive directions. Green denotes areas with the least deviations from the reference data, while blue indicates negative deviations. Yellow to red signifies positive deviations.

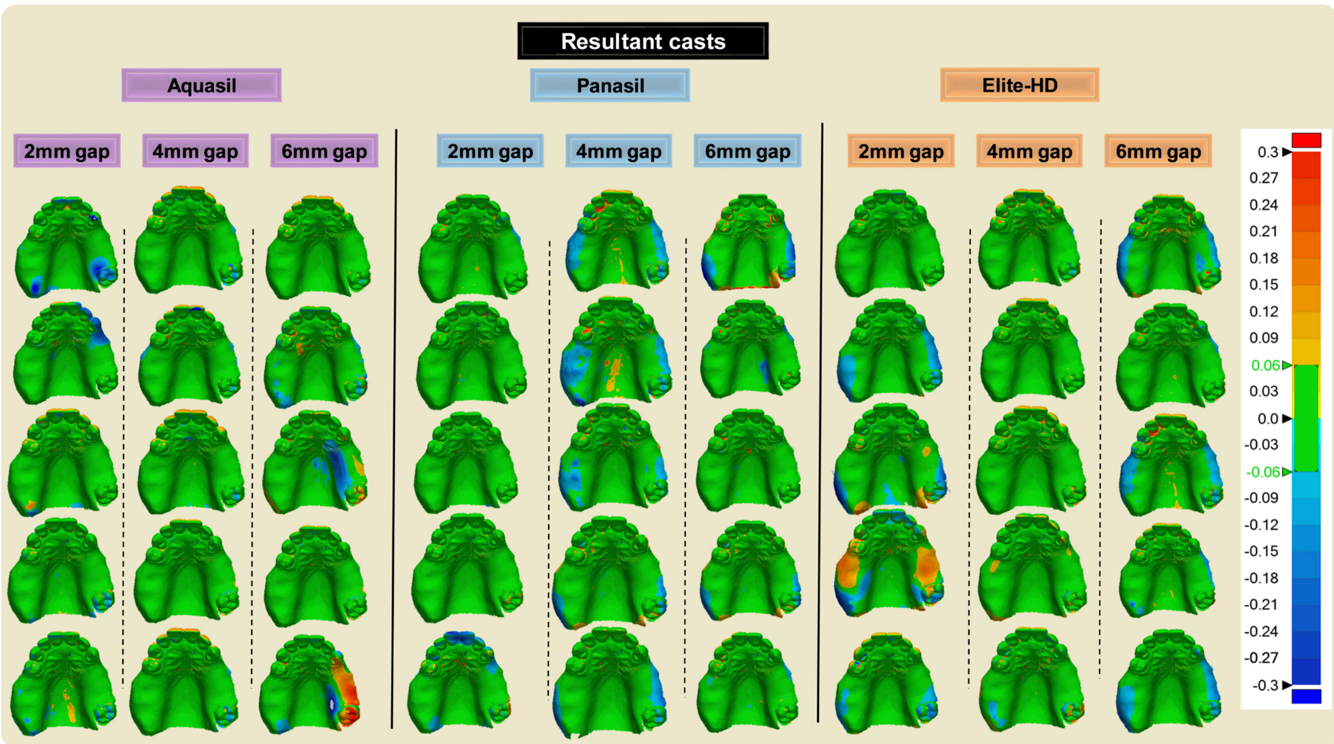

Figure 5: Color map analysis of the resultant casts from three addition silicone impressions (Aquasil, Panasil, Elite-HD) with three gap thicknesses; 2 mm, 4 mm, and 6 mm. Color map scale was adjusted to 300 μm in negative and positive directions. Green denotes areas with the least deviations from the reference data, while blue indicates negative deviations. Yellow to red signifies positive deviations.

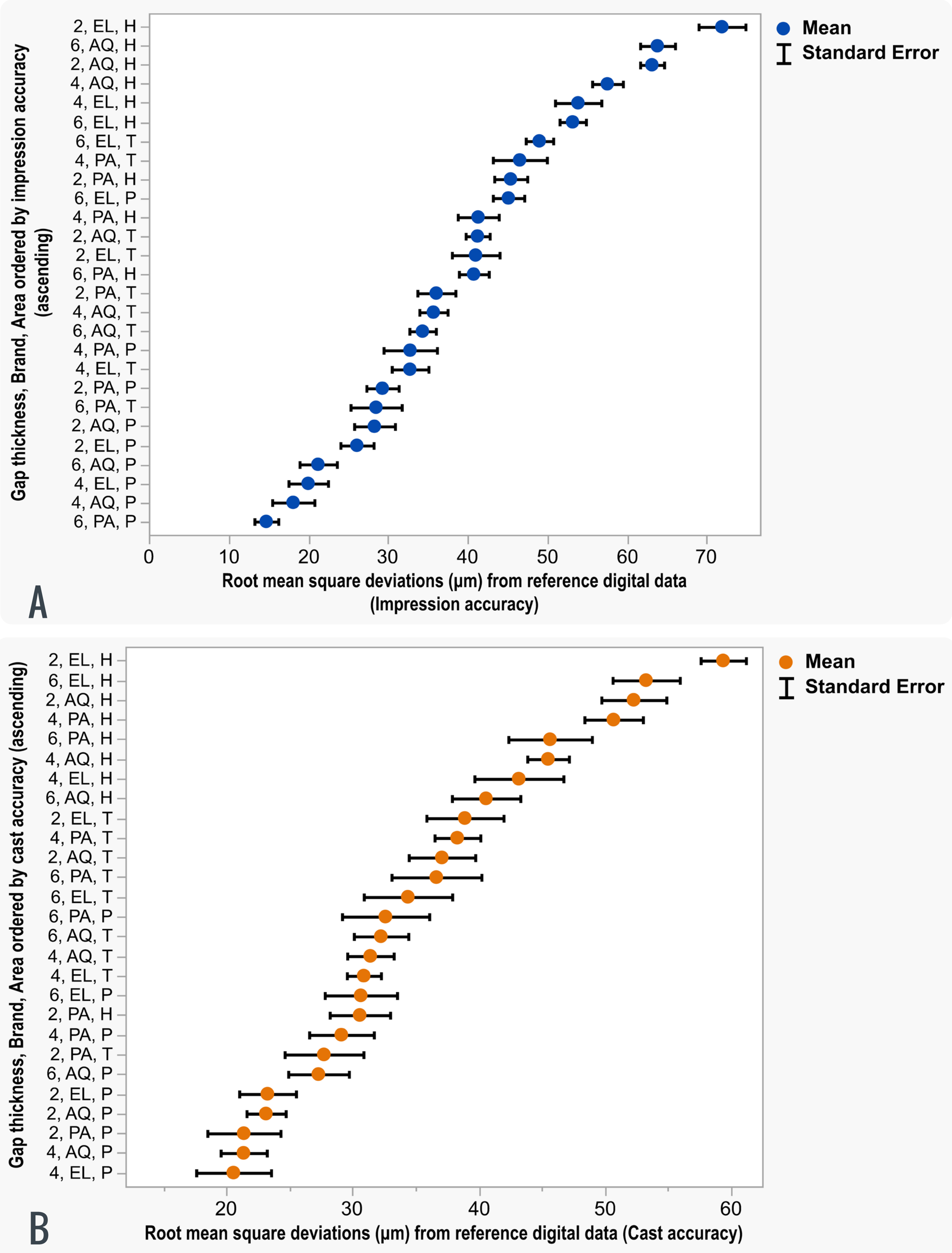

Figure 6: Root mean square (RMS) deviation values (μm) from the reference digital data for all impression and casts groups among all gap thicknesses in the total, palatal, and horseshoe areas. A: graph represents impression accuracy. B: graph represents cast accuracy. Each error bar is constructed using 1 standard error from the mean. Gap thicknesses are presented with numbers and letters where 2, 4, and 6 represent 2 mm, 4 mm, and 6 mm gap thicknesses. Brand represents impression material brand where AQ represents Aquasil, PA represents Panasil, and EL represents Elite-HD. Area represents the area evaluated where H denotes horseshoe area, P denotes palatal area, and T denotes total area

Table 2. Post-hoc Tukey HSD represents the least square mean differences for impression accuracy. The analysis includes the impression values for interactions between the impression gap thickness, impression material, and area. Columns not connected by same letter (from A to N) are significantly different ($P < 0.001$). Gap thicknesses are presented with numbers and letters where 2, 4, and 6 represent 2 mm, 4 mm, and 6 mm gap thicknesses. Brand represents impression brand where AQ represents Aquasil, PA represents Panasil, and EL represents Elite-HD. Area represents the area evaluated where H denotes horseshoe area, P denotes palatal area, and T denotes total area.

Gap thickness	Brand	Area	Connecting letters (A to N)														Least Squares Mean
6	PA	P														N	14.720000
4	AQ	P													M	N	18.100000
4	EL	P													M	N	19.980000
6	AQ	P												L	M	N	21.220000
2	EL	P											K	L	M	N	26.100000
2	AQ	P										J	K	L	M		28.300000
6	PA	T									I	J	K	L	M		28.500000
2	PA	P								H	I	J	K	L	M		29.300000
4	EL	T							G	H	I	J	K	L			32.760000
4	PA	P							G	H	I	J	K	L			32.780000
6	AQ	T						F	G	H	I	J	K				34.340000
4	AQ	T						F	G	H	I	J	K				35.700000
2	PA	T						F	G	H	I	J	K				36.060000
6	PA	H					E	F	G	H	I	J					40.760000
2	EL	T					E	F	G	H	I						41.000000
2	AQ	T					E	F	G	H							41.240000
4	PA	H				D	E	F	G	H							41.320000
6	EL	P			C	D	E	F	G								45.120000
2	PA	H			C	D	E	F									45.400000
4	PA	T			C	D	E	F									46.540000
6	EL	T			C	D	E										49.000000
6	EL	H		B	C	D	E										53.180000
4	EL	H		B	C	D											53.860000
4	AQ	H		B	C												57.540000
2	AQ	H	A	B													63.140000
6	AQ	H	A	B													63.820000
2	EL	H	A														71.920000

Table 3. Post-hoc Tukey HSD represents the least square mean differences for model accuracy. The analysis includes the impression values for interactions between the impression gap thickness, impression material, and area. Columns not connected by same letter (from A to J) are significantly different ($P < 0.001$). Gap thicknesses are presented with numbers and letters where 2, 4, and 6 represent 2 mm, 4 mm, and 6 mm gap thicknesses. Brand represents impression brand where AQ represents Aquasil, PA represents Panasil, and EL represents Elite-HD. Area represents the area evaluated where H denotes horseshoe area, P denotes palatal area, and T denotes total area.

Gap thickness	Brand	Area	Connecting letters (A to J)										Least Squares Mean
4	EL	P										J	20.540000
4	AQ	P										J	21.340000
2	PA	P										J	21.360000
2	AQ	P									I	J	23.120000
2	EL	P									I	J	23.240000
6	AQ	P								H	I	J	27.280000
2	PA	T								H	I	J	27.720000
4	PA	P							G	H	I	J	29.100000
2	PA	H							G	H	I	J	30.560000
6	EL	P							G	H	I	J	30.640000
4	EL	T							G	H	I	J	30.880000
4	AQ	T						F	G	H	I	J	31.400000
6	AQ	T					E	F	G	H	I	J	32.240000
6	PA	P					E	F	G	H	I	J	32.600000
6	EL	T					E	F	G	H	I	J	34.380000
6	PA	T				D	E	F	G	H	I		36.640000
2	AQ	T				D	E	F	G	H	I		37.080000
4	PA	T			C	D	E	F	G	H			38.300000
2	EL	T			C	D	E	F	G	H			38.900000
6	AQ	H		B	C	D	E	F	G	H			40.580000
4	EL	H		B	C	D	E	F	G				43.180000
4	AQ	H	A	B	C	D	E	F					45.500000
6	PA	H	A	B	C	D	E						45.660000
4	PA	H	A	B	C	D							50.700000
2	AQ	H	A	B	C								52.300000
6	EL	H	A	B									53.280000
2	EL	H	A										59.400000

DISCUSSION

Two hypotheses were tested in this study. The first hypothesis proposed that impression gap thickness would have no effect on the accuracy of the three tested impression materials or their resultants casts. However, the results indicated that gap thickness significantly influenced both impression accuracy and cast accuracy across all impression brands and evaluated regions as well as the interaction among these factors ($p < 0.001$). Consequently, the first hypothesis was rejected. The second hypothesis posited that the accuracy levels of the palatal and horseshoe areas would be similar. The findings demonstrated that the horseshoe area had significantly higher deviations compared to the palatal area ($p < 0.001$), leading to the rejection of the second hypothesis.

The 3D analysis employed in this study enabled a comprehensive assessment of both impressions and their corresponding casts by capturing linear and volumetric deviations across anatomically complex regions. This methodology offers improved clinical relevance over traditional one- or two-dimensional measurements by more accurately reflecting spatial distortion.[36,39-41] To differentiate sources of dimensional inaccuracy, both impressions and resultant stone casts were scanned. Conventional techniques are limited in their ability to isolate distortions originating from the impression material itself. Scanning the impressions directly allowed evaluation of the material's inherent dimensional stability, independent of variables introduced during cast fabrication. In contrast, scanning the cast enabled detection of additional deviations potentially caused by setting expansion of the gypsum or chemical interactions at the material-gypsum interface. For example, Panasil exhibited excellent accuracy at a 6-mm spacer in the impression scan, yet increased discrepancies were noted in the corresponding cast. This divergence suggests a material-specific interaction with gypsum that may compromise accuracy during cast fabrication. The dual-scan approach thus allowed for a stage-specific analysis of distortion, offering insights that would not have been achievable through evaluation of stone casts alone.

The horseshoe region, including anterior teeth and labial undercuts, is particularly prone to distortion during impression removal due to tensile forces acting on undercut areas, which may explain the consistently higher deviations observed in this region across all materials and spacer thicknesses.[24,47] Material properties, including hardness and rigidity, have been associated with impression removal difficulty.[30,33,48-50] In the present study, Panasil exhibited lower deviation values in the horseshoe region when compared to Aquasil and Elite-HD, which might suggest easier removal and reduced stress during impression detachment. However, Shore A hardness testing (please refer to the supplementary material available online, *Figure S2* and *Tables S1-S2*) revealed that Elite-HD had the highest hardness values across all measured time points, followed by Panasil and Aquasil. The greater force potentially required to remove Elite-HD impressions at 2 mm and 6 mm tray spacings may have contributed to higher levels of distortion in critical areas. Nonetheless, prior studies have shown that hardness and rigidity do not reliably predict the actual difficulty of impression removal or the dimensional accuracy of impressions.[33] Furthermore, the use of tray adhesive combined with mechanical interlocking via tray perforations may have induced stress concentrations toward the periphery of the impressions during removal, potentially explaining the localized deviations observed, especially in the horseshoe region.[51,52]

Impression and cast accuracy varied with spacer thickness and material brand. Aquasil and Elite-HD demonstrated optimal dimensional accuracy at a 4-mm spacer, particularly in the palatal region. In contrast, increased deviations were observed at both 2-mm and 6-mm spacer thicknesses. These outcomes are consistent with previous studies suggesting that minimal material thickness may restrict flow and adaptation, whereas increased thickness may amplify polymerization shrinkage or thermal contraction effects.[27,28,53] In this study, environmental variables were stringently controlled to minimize confounding factors. Thermal expansion was addressed by maintaining a stable room temperature (32°C ± 2°C) throughout the experimental process. Compared to Aquasil and Elite-HD, which both showed optimal accuracy at a 4-mm spacer for both impressions and casts, Panasil exhibited a divergent trend. Its most accurate impressions were obtained with a 6-mm spacer, while the corresponding cast demonstrated the highest accuracy at a 2-mm spacer. This discrepancy suggests a potential material-specific interaction between Panasil and gypsum slurry during cast fabrication. While no macroscopic anomalies were observed during pouring, FTIR spectroscopy (*Supplementary Figure S1*) revealed a broad OH stretching peak in Panasil, indicative of alcohol-based surfactants. Hydroxyl (-OH) functional groups are associated with increased hydrophilicity, which may enhance detail capture in moist environments, thereby improving impression accuracy. However, these polar components may also chemically interact with calcium sulfate during the setting of gypsum, potentially affecting surface reproduction or dimensional stability. Further investigation is warranted to elucidate the underlying physicochemical mechanisms and assess their clinical implications.

The impression accuracy of the entire arch (total area) in this study ranged from 28.5 ± 7.2 μm to 49 ± 3.9 μm, while cast accuracy ranged from 27.7 ± 6.9 μm to 38.9 ± 6.8 μm, regardless of the impression material or gap thickness. These results are consistent with previously reported ranges of 10-60 μm for complete arch definitive casts,[18-20,55,56] and 10-30 μm in other investigations.[17] However, direct comparisons remain limited, as earlier studies often assessed accuracy indirectly through stone casts, whereas the current study employed direct digital evaluation of both impressions and casts. Variations in materials, tray designs, impression techniques, and analytical protocols further complicate cross-study comparisons.

The findings of this study provide clinically relevant guidance for selecting impression materials and tray spacing based on the intended prosthodontic workflow. For digital workflows involving direct scanning of impressions, Panasil at 6-mm spacing demonstrated the highest dimensional accuracy across all evaluated regions. In contrast, for conventional workflows involving stone cast fabrication or scanning, Elite-HD at 4-mm spacing provided the best accuracy in the palatal region, while Panasil at 2 mm yielded the most accurate outcomes across the full-arch and dentulous-edentulous areas. These results highlight the importance of tailoring impression protocols to the specific fabrication method to achieve optimal dimensional accuracy. Although prior literature supports the notion that thinner impression layers (≤2 mm) tend to reduce dimensional inaccuracies, comparisons to existing studies must be made cautiously. For example, Gilmore *et al.*[54] evaluated impression accuracy using stainless-steel die and micrometer microscopy, a fundamentally different methodology from the 3D digital analysis employed in the present study. Hence, differences in experimental design, materials, and evaluation techniques limit the direct comparability of findings.

While earlier literature has suggested that impression accuracy may be largely operator-dependent and of limited standalone clinical value,[57] this study implemented standardized *in vitro* protocols to minimize such variability. Importantly, no universally accepted dimensional accuracy threshold exists for conventional impressions or casts used in fabricating fixed and removable prostheses. As a result, accuracy is typically assessed in relation to clinically acceptable prosthesis fit. Reported thresholds for cumulative manufacturing discrepancies range up to 311 µm for removable partial dentures,[58] and between 18-119 µm for fixed restorations.[59,60] Given this context, the dimensional deviations observed in the present study fall well within clinically acceptable limits for both applications.

The observed variation in material performance may be attributed to differences in chemical formulation, filler content, and physicomechanical properties *(Table 1)*. For instance, Panasil exhibited greater hydrophilicity, evidenced by a pronounced OH stretching peak in FTIR spectra, whereas Elite-HD showed the highest Shore A hardness values (*Supplementary Figures S1–S2*). Such distinctions in composition and performance reinforce the need for material-specific protocols, particularly when spacer thickness and workflow (digital vs. conventional) are considered. It has also been hypothesized that material color may influence optical scan accuracy due to differences in surface reflectivity, Aquasil being violet, Panasil blue, and Elite-HD yellow. Although direct evidence supporting this effect in dental PVS materials is lacking, digital imaging literature suggests that surface color and texture can affect scan resolution and accuracy.[61] Further investigation is needed to determine whether material color plays a clinically relevant role in digital impression workflows. Finally, operator technique, impression force, and the superimposition strategy employed in digital analysis may also introduce variability. Nevertheless, the significant differences observed among materials in this study are most plausibly explained by their distinct chemical and physical properties.

Although the evaluated impression materials, Aquasil, Panasil, and Elite-HD, are not explicitly marketed as “scannable,” the present study demonstrated their suitability for digital workflows. Dimensional accuracy did not differ significantly between impressions scanned with and without scanning spray (*Supplementary Figures S2 and S3*), confirming the materials’ compatibility with optical scanning systems. While prior investigations have validated the scannability of specific PVS materials, such as Elite-HD and other brands,[22,43] this study extends that evidence base by confirming comparable performance for Aquasil and Panasil. These findings support the use of these materials in digital impression techniques, although additional studies are recommended to evaluate scanner-specific and clinical variables that may influence scan accuracy.

This *in vitro* study offers valuable preliminary data; however, limitations must be acknowledged. The experimental conditions did not reproduce the full complexity of the intraoral environment, including variable moisture levels, soft tissue resilience, thermal fluctuations, and dynamic patient-related factors such as movement or saliva contamination. These elements may influence material behavior and clinical outcomes. This study was also limited to three commercially available hydrophilic PVS materials; each selected for their monophasic formulation and addition-cure mechanism. While this standardization minimized confounding variables and allowed for controlled comparisons, it also restricts the generalizability of the findings. Other categories of elastomeric materials, including polyether, condensation-cured silicones, or newer hybrid formulations combine characteristics of multiple material classes (e.g., polyether-silicone blends), may exhibit different dimensional responses under similar conditions. Future research should include a broader range of impression materials to validate these findings across diverse clinical systems. Future research should include a broader range of impression materials to validate these findings across diverse clinical systems. Moreover, the use of a single reference cast and specific tray type may not fully capture the variability encountered in clinical practice. Finally, while digital scanning methods were employed for high-resolution assessment, variations in scanner calibration and superimposition strategy may also affect accuracy measurements. Further *in vivo* studies with larger sample sizes, varied anatomical models, and broader material types are recommended to confirm the clinical relevance of these findings.

CONCLUSIONS

Impression gap thickness significantly affected the accuracy of both impressions and their corresponding casts across all tested addition silicone materials ($p < 0.001$). In digital workflows involving direct scanning of impressions, Panasil at 6-mm spacing produced the most accurate results across all evaluated regions. For conventional workflows involving stone cast fabrication or scanning, Elite-HD at 4 mm yielded the most accurate outcomes in the palatal region, while Panasil at

2 mm was most accurate in the full-arch and dentulous-edentulous regions. Across all materials and spacer conditions, deviations were more pronounced in the dentulous-edentulous region compared to the palate. These findings support material- and workflow-specific recommendations for improving impression accuracy in prosthodontic practice.

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SUPPLEMENTARY MATERIAL

While all three tested materials, Aquasil, Panasil, and Elite-HD, are marketed as hydrophilic addition silicones, their dimensional accuracy varied. Panasil consistently demonstrated superior accuracy across multiple anatomical regions. This disparity could not be explained by impression thickness alone, suggesting that other intrinsic material properties may contribute to performance differences. As noted in the introduction, factors such as chemical composition, surface wettability, polymerization kinetics, and post-polymerization hardness may all influence impression accuracy.

To investigate these aspects, a series of characterization experiments were conducted, focusing on selected physicochemical and mechanical properties. These included:

- Fourier-Transform Infrared (FTIR) Spectroscopy: To evaluate the chemical composition of each material, particularly the presence of functional groups or surfactants associated with hydrophilicity.
- Shore A Hardness Testing: To assess material hardness post-polymerization, which has implications for elastic recovery and dimensional stability.

FTIR SPECTROSCOPY ANALYSIS

FTIR spectra were obtained using a Perkin Elmer Spectrometer with a Horizontal Attenuated Total Reflectance (HATR) accessory. Spectral acquisition was performed over a range of 600-4000 cm-¹. A background spectrum was recorded before each sample measurement. Spectra were generated for:

1. The catalyst and base pastes of each material.
2. The fully set impression materials (Aquasil, Panasil, Elite-HD).

As illustrated in Figure S1, characteristic absorption bands were identified across all samples, including Si–H (2151.5 cm-¹) and Si–CH_3 (862.5 and 1254 cm-¹) bonds. All three materials exhibited a consistent peak at ~2957 cm-¹, corresponding to Si–CH_3 groups. Minor spectral differences were noted among the materials at 617, 1004, 1058, and 1193 cm-¹, likely reflecting differences in surfactants, filler types, or proprietary additives.

Panasil demonstrated a broad absorption peak at ~3401 cm-¹ in the uncured and partially cured states, attributed to –OH stretching typical of alcohol-based surfactants.[1] This peak diminished post-polymerization, suggesting that these polar functional groups may integrate into the crosslinked silicone

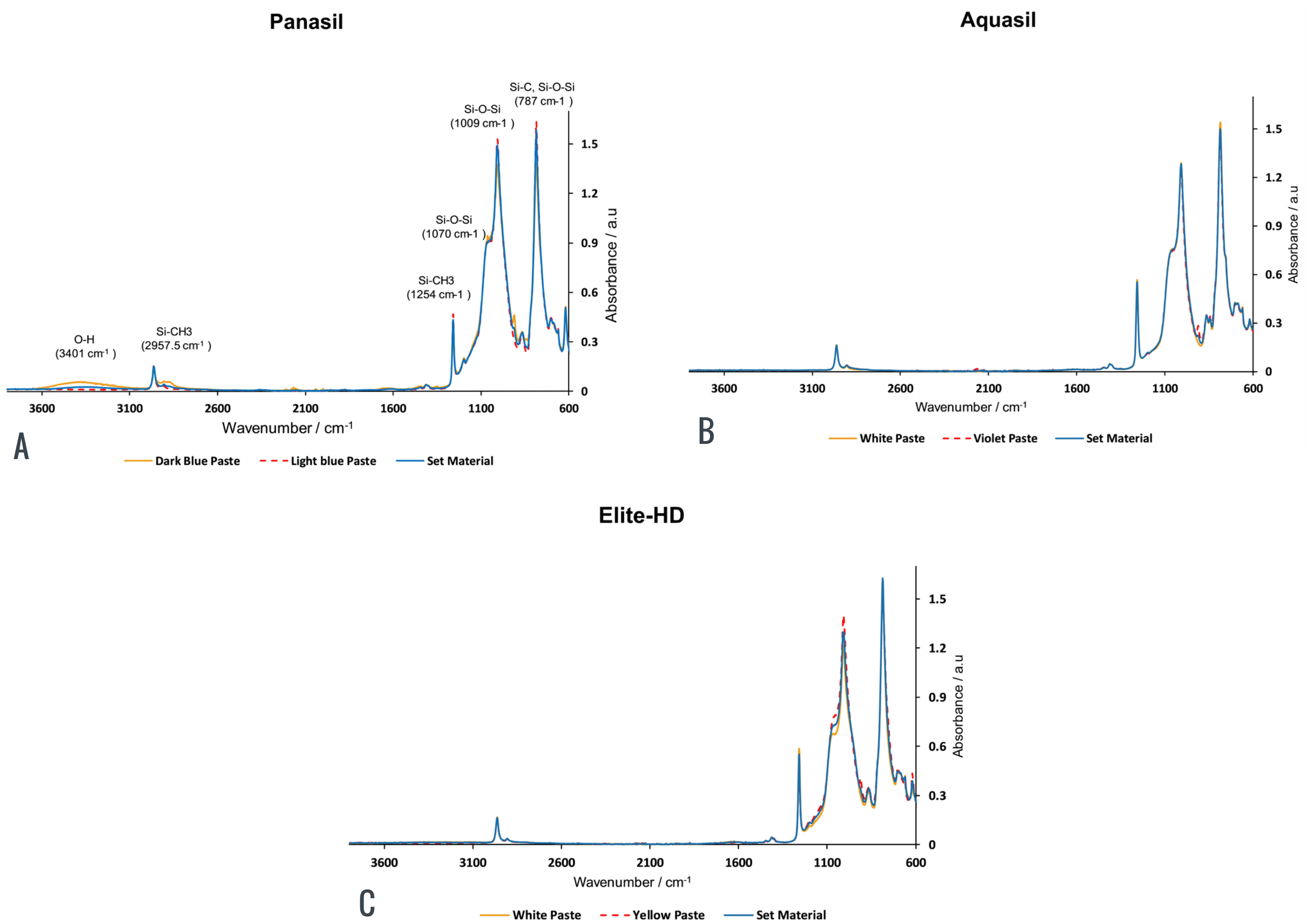

Figure S1: ATR-FTIR- spectrum of tested impression materials (Panasil, Aquasil, Elite-HD); base, catalyst and set material.

network during setting. Such a feature could enhance the hydrophilicity of Panasil and contribute to its superior performance in capturing surface detail.

SHORE A HARDNESS TESTING

The mechanical hardness of the set impression materials was evaluated using a Shore A durometer (H17A, Congenix Wallace, Kingston, UK). Twelve readings were taken for each material at four-time intervals following mixing:

- 1 hour
- 24 hours
- 72 hours
- 168 hours (7 days).[2]

As shown in Figure S2 and Table S1, Shore A hardness values increased significantly over time for all materials (ANOVA, $p < 0.001$). Elite-HD consistently exhibited the highest hardness values at all intervals, followed by Panasil and Aquasil (all pairwise comparisons, $p < 0.05$, and Table S2). These findings suggest that Elite-HD's higher hardness may have contributed to its relatively reduced accuracy in capturing fine anatomical detail, particularly in undercut regions.

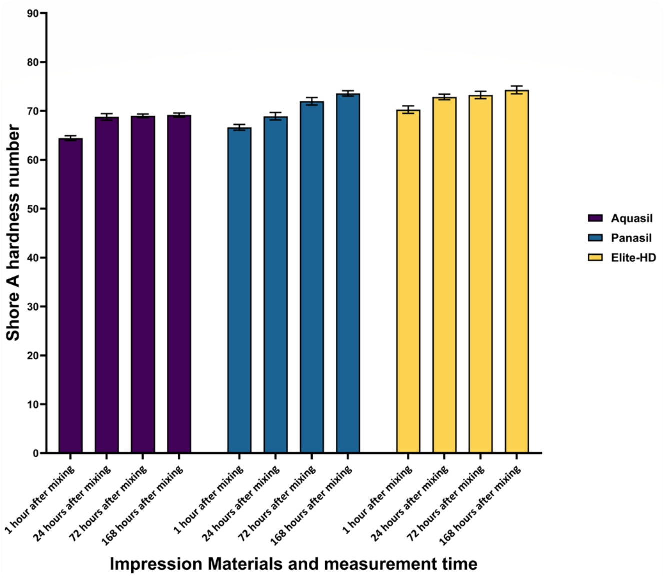

Figure S2: Shore A hardness of all impression materials; Aquasil, Panasil and Elite-HD at four different time points.

SCANNABILITY VALIDATION

To assess the materials' compatibility with digital workflows, three impressions per brand were scanned both with and without scanning spray. Root Mean Square (RMS) deviations were calculated relative to the digital reference cast for the total arch region. No statistically significant difference was observed between the two scanning conditions ($p > 0.05$), indicating that all tested materials were adequately scannable even in the absence of a scanning spray (see Supplementary Figures S3-S4).

Table S1. Tukey HSD test comparing shore A hardness values for Aquasil, Panasil, and Elite-HD impression materials at different time points after mixing. A significant difference was found when p < 0.05.

Tukey multiple comparisons test	Time after mixing	Adjusted P Value
Aquasil	1 hour after mixing vs. 24 hours after mixing	<0.001
	1 hour after mixing vs. 72 hours after mixing	<0.001
	1 hour after mixing vs. 168 hours after mixing	<0.001
	24 hours after mixing vs. 72 hours after mixing	0.839
	24 hours after mixing vs. 168 hours after mixing	0.458
	72 hours after mixing vs. 168 hours after mixing	0.919
Panasil	1 hour after mixing vs. 24 hours after mixing	<0.001
	1 hour after mixing vs. 72 hours after mixing	<0.001
	1 hour after mixing vs. 168 hours after mixing	<0.001
	24 hours after mixing vs. 72 hours after mixing	<0.001
	24 hours after mixing vs. 168 hours after mixing	<0.001
	72 hours after mixing vs. 168 hours after mixing	<0.001
Elite-HD	1 hour after mixing vs. 24 hours after mixing	<0.001
	1 hour after mixing vs. 72 hours after mixing	<0.001
	1 hour after mixing vs. 168 hours after mixing	<0.001
	24 hours after mixing vs. 72 hours after mixing	0.439
	24 hours after mixing vs. 168 hours after mixing	<0.001
	72 hours after mixing vs. 168 hours after mixing	<0.001

Table S2. Tukey HSD test comparing shore A hardness values between different impression materials: Aquasil, Panasil, and Elite-HD at different time points after mixing. A significance difference was found when P < 0.05.

Tukey multiple comparisons test	Materials	Adjusted P Value
1 hour after mixing	Aquasil vs. Panasil	<0.001
	Aquasil vs. Elite-HD	<0.001
	Panasil vs. Elite-HD	<0.001
24 hours after mixing	Aquasil vs. Panasil	0.865
	Aquasil vs. Elite-HD	<0.001
	Panasil vs. Elite-HD	<0.001
72 hours after mixing	Aquasil vs. Panasil	<0.001
	Aquasil vs. Elite-HD	<0.001
	Panasil vs. Elite-HD	<0.001
168 hours after mixing	Aquasil vs. Panasil	<0.001
	Aquasil vs. Elite-HD	<0.001
	Panasil vs. Elite-HD	0.022

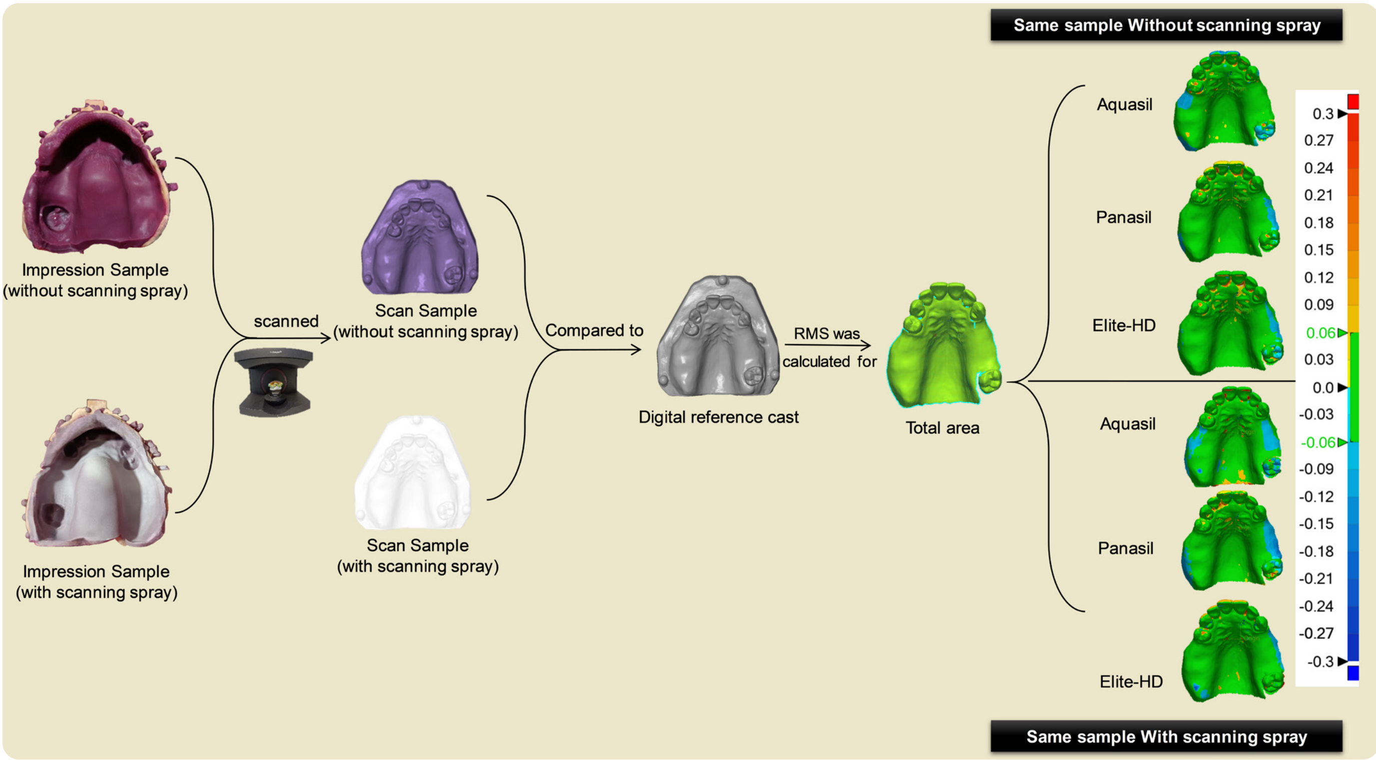

Fig. S3: A comparison of scanned impressions before and after scanning spraying with color heat maps showing the difference in the same sample in each impression material.

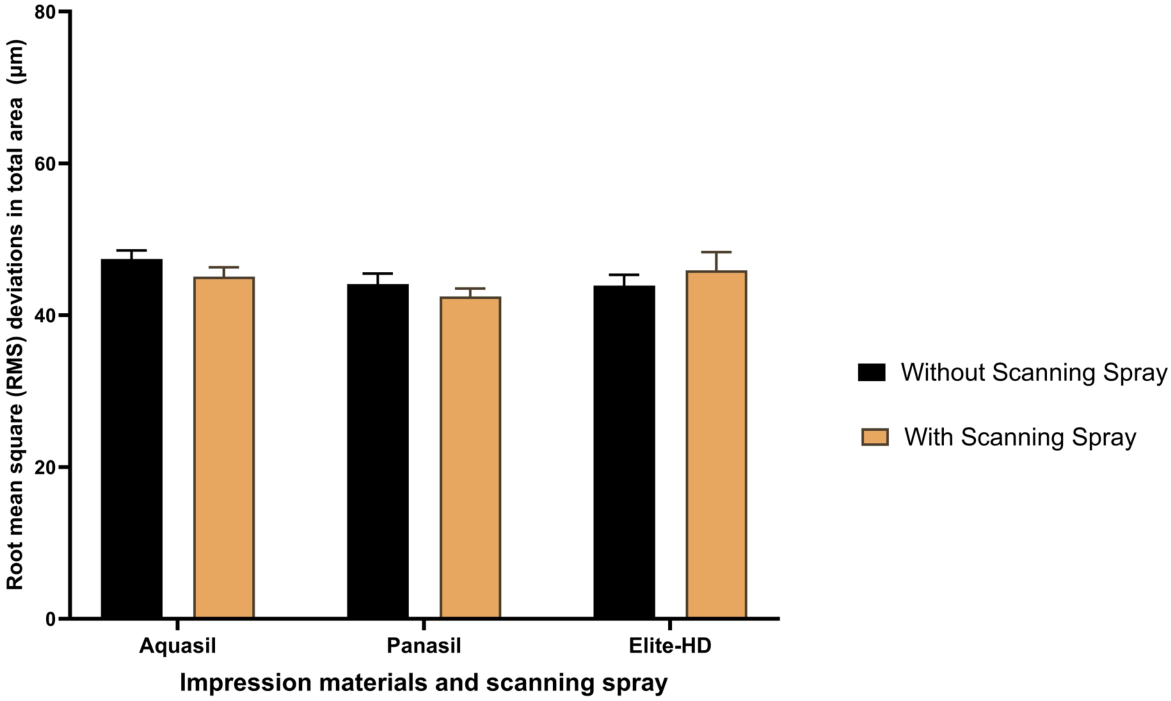

Fig. S4: Root mean square deviations (µm) from the reference digital cast in the total area when the impressions (Aquasil, Panasil, and Elite-HD) were scanned twice; with and without scanning spray.

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