Performance of dental impression materials: Benchmarking of materials and techniques by three-dimensional analysis

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Among other factors, the precision of dental impressions is an important and determining factor for the fit of dental restorations. The aim of this study was to examine the three-dimensional (3D) precision of gypsum dies made using a range of impression techniques and materials. Ten impressions of a steel canine were fabricated for each of the 24 material-method-combinations and poured with type 4 die stone. The dies were optically digitized, aligned to the CAD model of the steel canine, and 3D differences were calculated. The results were statistically analyzed using one-way analysis of variance. Depending on material and impression technique, the mean values had a range between +10.9/–10.0 μm (SD 2.8/2.3) and +16.5/–23.5 μm (SD 11.8/18.8). Qualitative analysis using color-coded graphs showed a characteristic location of deviations for different impression techniques. Three-dimensional analysis provided a comprehensive picture of the achievable precision. Processing aspects and impression technique were of significant influence.

Keywords: Dental impression precision, Polyethers, Silicones, Hydrocolloids, Vinyl polysiloxanethers

INTRODUCTION

Three-dimensional (3D) computer-aided analyses can be used for a wide variety of planning, treatment, and research applications, and have been used in dentistry as early as the mid-1980s¹. The gateway to the digital world is 3D data acquisition. Data can be acquired from different sources, such as non-contact optical digitizing, mechanical digitizing, or data from more complex medical imaging methods (e.g., computer tomography and magnetic resonance tomography). Such data and data captured at different times must be aligned from the relative measuring orientation into a common coordinate system before any analysis may be initiated^{1–4}.

Different impression materials for study models used in orthodontic treatment planning may be analyzed using cone-beam computer tomography data of the impressions⁵ with sufficient precision for orthodontic means. Alternatively, the impressions can be poured and the resulting gypsum models can be optically digitized⁶.

The analysis of materials for final impressions requires the use of micro-computed tomography ($\mu\text{-CT}$) data⁷ or non-contact optical digitizing based on the projection, reflection and detection of structured light and from different light sources. The latter can be applied for the detection of small differences, as found in the comparison of implant impression techniques⁸, changes in gypsum materials over time⁹, the accuracy of impression techniques¹⁰, or the influence of impression material type¹¹.

High-precision touch-probe digitizers can be used for mechanical digitizing¹² as long as the materials to be examined are not prone to wear or insufficient resistance against the contact pressure applied with the probe of

the mechanical digitizer¹³. Making replicas from the object to be analyzed allows for reinforcement with supporting materials, and can be used for a complete surface mapping with an electrical probe and an X-Y table¹⁴.

Often, the accuracy of different elastomeric impression materials for final impressions (e.g., fast-setting, silicones, vinyl siloxanethers) is assessed by measuring intra- and inter-arch distances of study models^{15–17} or by analyzing distances and angles of single abutments with specified geometrical dimensions^{18,19}. Image analysis of tooth contours allows for free-form shape analysis of the more complex geometries of prepared teeth^{20,21}. Distance measurements of arches and abutments are also used for the analysis of factors other than the impression material itself: impression technique^{22–27}, impression tray^{28,29}, material volume^{30–32}, or the effect of using a surfactant prior to pouring an impression³³.

Even when 3D digital data are used, the following analysis is often reduced to two-dimensional (2D) distance measurements^{4,34}. This type of analysis implies a loss of information and may not account for the variability of dimensional accuracy as it relates to measurement site³⁵. The comparison of 2D and 3D accuracy of dental impression materials revealed dimensional discrepancies in the 3D analysis that were not found in the 2D analysis³⁶. The full picture of the dimensional accuracy can only be achieved with 3D analyses, which should be used for the characterization of the dimensional stability and accuracy of impression materials, especially where materials for final impressions are concerned³⁶.

Three-dimensional *in vitro* analyses overcoming the 2D limitations focused on different impression

materials^{7,11,12,37}, impression techniques¹⁰, impression trays^{34,38}, and aspects of implant impression accuracy^{8,36,39,40}.

Because of a greater tolerance towards dimensional changes, the requirements for impression materials for diagnostic casts differ from those for final impressions. Impressions made with irreversible hydrocolloids should be poured immediately, as delayed pouring negatively influences their dimensional stability and precision^{41,42}.

Elastomeric impression materials available for final impressions are vinyl siloxanether, vinyl polysiloxane, silicone (usually addition-curing, but also available as condensation-curing materials), and polyether. They are still the most common method of transferring information from the patient to the dental laboratory when making indirect restorations⁴³. The most accurate elastomeric impression materials available are polyvinyl siloxanes, polyethers, and vinyl siloxanethers^{15,17,44}. For single teeth or small segments (up to four teeth), a clinically achievable precision of up to ± 40 – $50\text{ }\mu\text{m}$ can be deduced for the mean deviations from clinical trials^{45–47}.

In vitro evaluations result in higher precision and mean dimensional changes below $\pm 20\text{ }\mu\text{m}$ ^{27,48}. In contrast to single teeth or small segments, *in vitro* full arch impressions made with polyether applying a 3D analysis showed a precision of $61.3 \pm 17.9\text{ }\mu\text{m}$ ⁴⁹.

By combining quantitative and qualitative information on the complete surface of a prepared tooth, limitations such as the need for an additional macroscopic evaluation of detail reproduction³⁵ can be overcome. The experimental setup will have to render an adequate representation of the complex preparations encountered in clinical dentistry^{36,50}. While μ -CT data can overcome the limited accuracy of non-contact optical digitizing in narrow and deep areas such as pits, fossae or the cervical margins of teeth⁷, there will be confined access to appropriate tomography devices. Furthermore, hardening artifacts, which can be caused by metal pins commonly used for saw-cut master models could be an obstacle analog to the presence of metal prostheses in CT images⁵¹. Common dental non-contact digitizing devices will be much more easily available and less expensive. They generally show sufficient accuracy⁵². In combination with commercially available 3D analysis software, the proposed experimental setup can be rather effortlessly adapted by different research groups¹¹ and independently of changing staff.

Adapting a method developed by Luthardt *et al.*⁹, the experimental setup presented here aims at a 3D analysis allowing for a benchmarking of a wide range of different impression materials and impression techniques, thus providing a more complete three-dimensional (3D) picture of the achievable quantitative and qualitative dimensional accuracy.

MATERIALS AND METHODS

The experimental set-up is based on a master model and its identical virtual CAD model (Fig. 1). From a stainless steel master model with a circular chamfer preparation

(upper canine) impressions were made with a range of impression materials: condensation-curing silicone (cs), irreversible hydrocolloid (ih), polyether (pe), reversible hydrocolloid (rh), vinyl polysiloxane (vps), vinyl (poly) siloxanether (vpse); and different impression techniques: monophasic (m), one-stage two-phase (o), two-phase putty and wash (t), diagnostic cast impressions (d), manual mixing (man), auto-mixing (aut) (Tables 1a and 2). Ten duplicate dies were made for each material/technique combination. All impressions and duplicate gypsum dies were made at room temperature (21°C) in a dental office or dental laboratory environment respectively. These were optically digitized with a high-precision digitizing system (ODKM 97, Fraunhofer Institute for Applied Optics and Precision Engineering, Jena, Germany). The measurement uncertainty as given by the manufacturer was $\sim 8\text{ }\mu\text{m}$. Measurements resulted in data sets with around 70,000 data points ($\pm 5,000$) per die. The data sets were aligned to the virtual CAD model. Afterwards, the 3D differences were quantitatively and qualitatively analyzed.

Impression making

Individualized custom trays divided into small compartments with pattern resin (Palavit G, Heraeus Kulzer, Hanau, Germany) or, if requested by the manufacturer, individual light-curing resin trays (Triad VLC Löffelmaterial, Heraeus Kulzer, Hanau, Germany), were used as impression trays.

Wire rests (for most impressions, two short straight pieces of orthodontic wire laid across the impression tray parallel to one another in vestibular-oral direction) or an adjustable mount to which the steel master model was attached at its base and then lowered into the compartment holding the impression material (for diagnostic cast impressions) ensured that the master model and the preparation margin were fully covered with impression material but could not sink deeply into the impression material under its own weight. Proper tray adhesives (Table 1b) were applied in a thin layer, which was allowed to dry for 10 min.

For monophasic impressions, the tray was first filled with the respective impression material (Table 1a) and then the master model was covered with the same material from an application syringe in an upward spiral movement, starting at the chamfer. For one-stage two-phase impressions, the tray was first filled with the higher viscosity material (Table 1a) using an automatic mixing unit (Table 1b), and afterwards the master model was covered with the lower viscosity material (Table 1a) with the helical movement starting at the chamfer. An automix syringe was used for the lower viscosity materials. The covered master model was lowered into the tray material until the chamfer was completely covered or the wire rests were touched. The master model remained in the impression without applying any pressure for a time span according to the manufacturer's instructions plus an extra 3 min with regard to room temperature (instead of body temperature).

The two-phase putty and wash tray material was

Fig. 1 Evaluation procedure based on a master model and virtual CAD model (A) for quantitative and qualitative 3D analysis. Duplicate gypsum dies (C) are made from different impression materials/techniques (B). The digital data of the duplicate gypsum dies (D) are aligned to the virtual CAD model (A) before 3D differences are calculated (E).

mixed either with a mixing unit or by hand (according to the manufacturer's instructions) and filled into the prepared tray. After complete setting of the putty material, the master model was removed from the preliminary impression and checked for flaws. The material was cut back to the tray's rim. Four grooves were cut crosswise into the putty and the preparation margin was circularly removed. For the wash impression, the master model was covered as described before and reinserted into the preliminary impression.

Impressions with materials for diagnostic casts (Table 1a) were either automixed (Table 1b) or hand mixed. The powder/water ratio for the irreversible hydrocolloids was measured according to the manufacturer's instructions (9 g powder: 17.5 mL water). First, the powder was added to the mixing bowl and afterwards the water. A spatula was used to blend powder and water together for several seconds until moist.

The automix device was turned on. Holding the spatula firmly and positioning it at the top of the mixing bowl, it was moved at a straight line down to the center

of the bowl twice. The device was stopped, the spatula was cleaned at the rim of the bowl and the downward movement was repeated after turning the device on again, resulting in a machine mixing time of 15 s. The hand-mixed hydrocolloid was well stirred for 40 s until a homogeneous consistency was reached. The impression material was then filled into the tray compartment.

An addition-curing silicone for diagnostic cast impressions (Table 1a) was also mixed with a mixing unit (Table 1b).

All impressions were checked for flaws after removing the master model using 2.5× magnification glasses.

Manufacturing of duplicate gypsum dies

Impressions rested for 4 h after removal, to achieve optimal elastic recovery. The only exceptions were the reversible hydrocolloid precision impressions and the irreversible hydrocolloid diagnostic cast impressions, which were poured immediately after removing the steel master die. The impressions were poured a single time with class 4 gypsum (Esthetic-rock, Dentona DENTAL,

Table 1a Impression materials; number in this study, manufacturers, and LOT numbers

No.	Material	Material Type	Manufacturer (all Germany)	LOT No.
1	Dimension Garant L	Light body VPS	3M ESPE, Seefeld	FW0067062/FW0063829/ FW0066930
2	Dimension Garant L Quick			FW0065084/FW0067062/ FW0059154/FW0065065
3	Dimension Penta H			FW0061862/FW0058500/ FW0065699/103806
4	Dimension Penta H Quick Putty	Heavy-body VPS		FW0064055/FW0061225/ FW0058595/FW0065825
5	Express Penta Putty			165304
6	Express STD			20040614
7	Impregum Garant L DuoSoft	Light-body PE		B0004 2001-12/C0003 2001-12
8	Impregum Penta	Heavy-body PE		FW0061722/0066761/107638
9	Impregum Penta Soft			FW0061531/FW0061532
10	Imp. Penta Soft Quick Medium Body	Medium-body VPS		180453
11	Impregum L DuoSoft Quick	Light-body PE		174999/B194744/195967
12	Impregum Penta H DuoSoft Quick base	Heavy-body PE		195971/205895
13	Impregum Penta H DuoSoft Quick catalyst	Catalyst for heavy-body PE		196002/206405
14	Korsil	Heavy-body VPS		163388
15	Palgat plus quick	Irreversible hydrocolloid		Z0010673
16	Honigum Light	Light-body VPS	DMG, Hamburg	615401
17	Honigum MixStar Heavy	Heavy-body VPS		615614
18	Status blue			684350
19	Flexitime Dynamix Putty			340104
20	Flexitime Fast&Scan Dynamix Putty	Light-body VPS	Heraeus Kulzer, Hanau	330446
21	Flexitime Fast&Scan Light Flow			330142
22	Flexitime Fast&Scan Medium Flow	Medium-body VPS		330137
23	Flexitime Light Flow	Light-body VPS		330034
24	Flexitime Medium Flow	Medium-body VPS		330410
25	Optosil P plus	Heavy-body CS		180137
26	Xantopren VL plus	Light-body CS		190097
27	Identium Heavy	Heavy-body VPS	Kettenbach, Eschenburg	110201-35
28	Identium Medium	Medium-body VPS		110181-59
29	Identium Light	Light-body VPS		110071
30	Panasil binetics contact x-light			110291-28
31	Panasil binetics putty fast	Heavy-body VPS		110621-185

Table 1b Adhesive liquids; manufacturers, LOT numbers, and mixing units. For material numbers please refer to Table 1a

Tray adhesives	Used for materials	Manufacturer	LOT No.
Polyether Adhesive	8-9, 12	3M ESPE, Seefeld	FW0067100
Universal Adhesive	3-6, 10, 14, 17-20, 22, 24, 25	Heraeus Kulzer, Hanau	300699/340084
Identium Adhesive	27, 28	Kettenbach, Eschenburg	R1000325
Panasil Haftlack	31		R1100308
Fix Adhesive – Liquid	15	Dentsply DeTrey, Konstanz	1109001598
Mixing units	Used for materials	Manufacturer	
Pentamix 2	3-6, 8-10, 12, 14, 17, 25	3M ESPE, Seefeld	
Pentamix 3	18		
Dynamix Mischgerät	19, 20, 22, 24	Heraeus Kulzer, Hanau	
Sympress Dispenser	27, 28, 31	Kettenbach, Eschenburg	
Alginator	15	DUX Dental, Utrecht, The Netherlands	

Wipperfurth, Germany). The water/gypsum ratio was measured with digital scales and a measuring cup according to the manufacturer's instructions (20 mL water with 100 g gypsum), with demineralized water being used and mechanical vacuum-mixing for 60 s. Laboratory surfactants were not applied. After shortly rinsing the impressions with water, excess water was removed with a gentle stream of air, avoiding over-drying.

Four hours after pouring, the duplicate dies were removed and checked for flaws using the magnification glasses. Dies from final impressions that showed bubbles, voids, or those that were discolored were discarded. In the case of diagnostic cast impressions, bubbles and small gypsum pearls resulting from bubbles in the impression material were tolerated. Excessive gypsum material was removed with dry trimming only to avoid expansion after setting.

3D analysis

After digitizing, all measuring points clearly below the die's preparation margin—the parts of the die belonging to its base—were removed manually. The system software (ARGUS, Fraunhofer Institute for Applied Optics and Precision Engineering, Jena, Germany) was used for data handling. Outlier data points were removed (parameters: tolerance 200%, minimum of 25 connected points) and an automatic filtering algorithm was applied (stray points removal with parameters: tolerance 400%, kernel 4 and size 4). The file format for data export was *.asc (ASCII, American Standard Code for Information Interchange). This format can be read by a computer-aided design and analysis software (Surfacer 10.6, Imageware Inc., Ann Arbor, MI, USA). Data quality was further improved by using semi-automatic specific filtering algorithms for outliers and stray data points, which were iteratively developed

(threshold, checking distance, planar or spherical filter) in previous studies^{3,9,53}. The procedure removes points from the selected point clouds that do not conform to local planar or spherical models that are specified by other points in their neighborhood. This function samples the data based on agreement with locally fit models. Two model types may be used: a planar model and a spherical model. For each point, the function computes the local neighborhood model and checks the distance between the point and the model. If the distance is larger than the specified tolerance distance, the point is identified as an outlier and is rejected. The threshold for the neighborhood size was set to 0.010 mm and the maximum deviation tolerated was 0.001 mm. The cut back and filtered data sets afterwards consisted of about 60,000 measuring points each.

All digitized dies were oriented in a coordinate system of their own and had to be aligned to the virtual CAD model (best-fit registration) before a 3D analysis was possible (Surfacer and Geomagic Studio 9, Geomagic Inc., Research Triangle Park, NC, USA). The alignment or registration is a software algorithm calculation of the vector or the matrix for the three-dimensional movement of the digitized gypsum duplicate dies to the reference CAD model representing the steel master die. The calculation is based on the determination of the best-fit between each of the 60,000 data points per digitized gypsum die and the reference CAD model by computing the respective perpendicular to the reference CAD surface. The calculation was performed with a tolerance setting of 0.0001 mm. Alignment precision was recorded as root mean square (RMS) error.

After the best possible alignment between each duplicate die and the reference CAD model had been reached, the calculation of differences was done by using the 3D analysis feature of the CAD software. As output data, the computation provided quantitative

Table 2 Product names, impression techniques, abbreviation used for each group of ten gypsum duplicate dies, and mean positive and negative deviations [mm] from the virtual CAD model

Product name	Impression technique	Abbreviation	Mean positive deviation [mm]	Mean negative deviation [mm]
Impregum Penta Soft	monophase (m)	pe-m-imps	0.0145 ^{c, d, e}	−0.0135 ^{j, k, l}
Impregum Penta	monophase (m)	pe-m-imp	0.0118 ^{b, c, d}	−0.0097 ^{j, k, l, m}
Impregum Penta Soft Quick Medium Body	monophase (m)	pe-m-impsq	0.0134 ^{b, c, d, e}	−0.0131 ^{j, k, l, m}
Identium Medium	monophase (m)	vpe-m-idenm	0.0117 ^{b, c, d}	−0.0081 ^m
Impregum Penta H/Garant L DuoSoft	one-stage two-phase (o)	pe-o-impduo	0.0108 ^{b, c, d}	−0.0120 ^{j, k, l, m}
Dimension Penta H/Garant L	one-stage two-phase (o)	vps-o-dim	0.0092 ^b	−0.0085 ^{l, m}
Impregum Penta H/L DuoSoft Quick	one-stage two-phase (o)	pe-o-impduoq	0.0119 ^{b, c, d}	−0.0124 ^{j, k, l, m}
Systoloid	one-stage two-phase (o)	rh-o-sys	0.0090 ^b	−0.0117 ^{j, k, l, m}
Honigum Heavy/Light Body	one-stage two-phase (o)	vps-o-hon	0.0111 ^{b, c, d}	−0.0115 ^{j, k, l, m}
Identium Heavy/Light	one-stage two-phase (o)	vpe-o-idenhl	0.0131 ^{b, c, d, e}	−0.0081 ^m
Flexitime Dynamix Putty/Light Flow	one-stage two-phase (o)	vps-o-flexpl	0.0103 ^{b, c}	−0.0089 ^{k, l, m}
Flexitime Dynamix Putty/Medium Flow	one-stage two-phase (o)	vps-o-flexpm	0.0145 ^{c, d, e}	−0.0098 ^{j, k, l, m}
Flexitime Fast und Scan Light Flow	one-stage two-phase (o)	vps-o-flexl	0.0103 ^{b, c}	−0.0087 ^{l, m}
Flexitime Fast und Scan Medium Flow	one-stage two-phase (o)	vps-o-flexm	0.0092 ^b	−0.0085 ^{l, m}
Palgat Plus manual	diagnostic cast impression (d)	ih-d-pal-man	0.0165 ^e	−0.0099 ^{j, k, l, m}
Palgat Plus automatic	diagnostic cast impression (d)	ih-d-pal-aut	0.0169 ^e	−0.0100 ^{j, k, l, m}
Status Blue	diagnostic cast impression (d)	vps-d-blue	0.0118 ^{b, c, d}	−0.0145 ^j
Dimension Penta H/Garant L Quick	two-stage putty and wash (t)	vps-t-dimq	0.0017 ^a	−0.0625 ^g
Korsil (experimental material)	two-stage putty and wash (t)	vps-t-em	0.0100 ^{b, c}	−0.0366 ^h
Express Penta Putty	two-stage putty and wash (t)	vps-t-expp	0.0154 ^{d, e}	−0.0186 ⁱ
Optosil P plus/Xantopren VL plus	two-stage putty and wash (t)	cs-t-opt	0.0318 ^f	−0.0121 ^{j, k, l, m}
Express STD	two-stage putty and wash (t)	vps-t-exps	0.0345 ^f	−0.0141 ^{j, k}
Honigum Heavy/Light Body	two-stage putty and wash (t)	vps-t-hon	0.0106 ^{b, c}	−0.0102 ^{j, k, l, m}
Panasil binetics putty fast/ initial contact x-light	two-stage putty and wash (t)	vpe-t-pan	0.0110 ^{b, c, d}	−0.0107 ^{j, k, l, m}

Letters in superscript indicate deviations belonging to one or more of six (positive: a–f) or seven (negative: g–m) different homogeneous subgroups identified with the Student-Newman-Keuls post hoc algorithm. Values with different letters are significantly different from one another, while values indexed with the same letter do not show any significant difference.

data (maximum positive deviations, mean positive deviations, mean negative deviations, maximum negative deviations, and a frequency distribution vertical-bar graph) as well as qualitative data in the form of color-coded graphs (color difference map), the latter showing the distribution of the 3D deviations over the complete surface of each gypsum die.

For better comparability, data were sampled to an even measurement point distance of 50 μm , resulting in $23,650 \pm 370$ points to be analyzed per die. A

perpendicular, the smallest distance from each measurement point to the virtual CAD model, was calculated using the CAD software. All points lying outside or above the CAD-models' surface were defined as positive deviations, while those lying inside or below this surface were defined as negative deviations. The values obtained for a series of 10 duplicate dies are reported as “mean positive deviation” and “mean negative deviation” respectively. In order to assess the complete 3D information and in addition to the

quantitative analysis, a qualitative analysis using color-coded graphs was performed. The ten data sets of each test series were added to one single data set for the calculation of the color graphs.

Statistical analysis

For comparison of the different impression materials and techniques, the median, minima, maxima, and the interquartile range of the mean positive and negative deviations are shown in box-and-whisker plots. One-way analysis of variance was used for statistical analysis at a level of significance of $\alpha=0.05$ (SPSS 20.0, IBM Corporation, Armonk, NY, USA). The Levene test for homogeneity of variances and the Student-Newman-Keuls (SNK) post hoc test algorithm for equal variance were applied.

RESULTS

In order to clearly differentiate between gypsum duplicate dies which are reduced in circumference or height and those dies which are enlarged in either dimension, positive and negative values will be reported separately in the following. While the negative most value would be mathematically correct be referred to as the minimum value, those values will be reported as “maximum negative” with regard to their clinical relevance and the later discussion.

The range of RMS error for monophase (4 groups), one-stage two-phase (10 groups), two-stage putty and wash (7 groups), and diagnostic cast impressions (3 groups) were 8.0–22.9 μm (mean for all monophase impressions: 15.8 μm , SD 5.4), 9.3–15.2 μm (mean for all one-stage two-phase impressions: 12.1 μm , SD 2.1), 11.9–39.0 μm (mean for all two-stage putty and wash

impressions: 23.9 μm , SD 10.3), and 13.8–14.8 μm (mean for all diagnostic cast materials/mixing techniques: 14.2 μm , SD 0.5), respectively.

Depending on the impression technique (without differentiation between the impression materials), the three-dimensional positive and negative mean deviations of all values for the monophase technique were +12.9/–11.1 μm (SD 3.4/3.6) and 3D maximum positive and negative deviation values were +83.6/–88.7 μm . For the one-stage two-phase technique, the 3D positive and negative mean deviation values of all impressions were +10.9/–10.0 μm (SD 2.8/2.3) and 3D maximum positive and negative deviation values of +207.3/–129.9 μm were found. The pooled two-stage putty and wash technique impressions showed mean positive and negative values of +16.5/–23.5 μm (SD 11.8/18.8) and maximum positive and negative values of +196.5/–154.9 μm . All of the diagnostic cast materials together resulted in mean positive and negative values of +15.0/–11.5 μm (SD 4.9/3.4), and maximum positive and negative values of +257.0/–20.6 μm .

The distribution of the deviations on the die surface is shown in color-coded graphs. Monophase impressions (Fig. 2: A), one-stage two-phase impressions (Fig. 2: B), and irreversible hydrocolloids for diagnostic cast impressions (Fig. 2: D) showed a circumferentially slightly enlarged representation of the master model and a rounding of edges. The dies were enlarged in height. Gypsum pearls resulting from bubbles can be found in irreversible hydrocolloids (darker red dots). Two-stage putty and wash impressions (Fig. 2: C) showed an elongation and a circumferential reduction. The latter was also found for addition-curing silicone for diagnostic cast impressions (Fig. 3: C).

Figures 4 (monophase, one-stage two-phase

Fig. 2 Qualitative analysis; typical examples for monophase (A), one-stage two-phase (B), two-phase putty and wash (C), and diagnostic cast impressions (D), the latter made with irreversible hydrocolloid.

Yellow to red colors show enlargement, blue colors show reduction in size. The typical deviations for monophase (A) and one-stage two-phase (B) impressions were circumferential enlargement, an elongation of the tip and a rounding and thus reduction of edges. In addition to bubbles shown as dark red spots, these effects are more pronounced in diagnostic cast impressions with irreversible hydrocolloid (D). In contrast, two-phase putty and wash impressions clearly showed a generalized circumferential reduction alongside an enlargement in height.

Fig. 3 Qualitative analysis; results for hand- (A) and machine- (B) mixed irreversible hydrocolloid in comparison to diagnostic cast impressions made with addition-curing silicone (C). Yellow to red colors show enlargement, blue colors show reduction in size. The dark red spots represent gypsum pearls resulting from bubbles in the impression material. While hand- and machine-mixed irreversible hydrocolloid impressions for diagnostic casts (A and B) showed circumferential enlargement, elongation of the tip and rounding and thus reduction of edges similar to high precision monophasic and one-stage two-phase impressions, the addition-curing silicone (C) for diagnostic casts showed a pronounced generalized circumferential reduction alongside an enlargement in height similar to some of the precision two-stage putty and wash impressions.

Fig. 4 Mean positive and negative deviations. Group on the left: monophasic (m) impression technique, middle: one-stage two-phase (o) impression technique, on the right: diagnostic cast impression materials (either vinyl polysiloxane (vps) or irreversible hydrocolloid (ih)). Benchmark was set to ± 0.02 mm. Outlier values are more than 1.5 times the box width away from the boxes' outer boundaries and are indicated by circles. Boxes with different letters are significantly different from one another, while those indexed with the same letter do not show any significant difference.

impression technique and diagnostic cast impressions) and 5 (two-stage putty and wash impression technique) as well as Table 2 (mean positive and negative deviations) show the results for the mean positive and negative deviations analyzed with one-way analysis of variance. For tests assuming equal variances such as the Student-Newman-Keuls (SNK) post hoc algorithm used here, homogeneous subsets can be constructed using a range determined by the specific test being used (Table 2). Six subgroups were determined for the mean positive deviations (a to f) and 7 subgroups (g to m) were found for the mean negative deviations by SNK.

Except for the only condensation-curing silicone tested in this study (cs-t-opt) and one of the vps materials (vps-t-exps), which both underwent the two-stage putty and wash impression technique, all mean positive deviations were below the benchmark of 0.02 mm ($\pm 20\ \mu\text{m}$). This also applies to the spread of values analyzing materials for final impressions when the monophase and one-stage two-phase impression technique were used, and for three of the seven material combinations that were used for the two-stage putty and wash impression technique. While the mean positive deviations of materials for diagnostic casts are also below the benchmark of $\pm 0.02\ \text{mm}$, these materials either show more widespread values or deviations above the benchmark. The spread of values and large mean negative deviations are especially pronounced for the vps-based diagnostic cast impression material.

The analysis of materials for the two-stage putty and wash impression technique generally showed larger mean negative deviations (vps-t-dimq, vps-t-em, vps-t-expp) or a wider spread of values and mean positive deviations above the benchmark of $\pm 0.02\ \text{mm}$ (cs-t-opt and vps-t-exps, $p < 0.000$). One material (vps-t-dimq) showed a particularly notable small mean positive deviation interlinked with larger mean negative deviations ($p < 0.000$). However, two material combinations (vps-t-hon and vps-t-pan) showed results comparable to the other impressions techniques tested ($p = 0.1197$).

While the mean positive differences between subgroups b and e (Table 2) were statistically significant, the value range between 0.009 and 0.0169 mm (9–17 μm) was rather small. A similar range was found for the mean negative deviations of subgroups j–m (Table 2). Again, differences were statistically significant ($p < 0.000$) but showed a small range with mean negative values between -0.0145 and $-0.0081\ \text{mm}$ (-15 to $-8\ \mu\text{m}$). Only three material combinations used for the two-stage putty and wash impression technique showed significantly higher mean negative values when compared with subgroups j–m: vps-t-dimq (subgroup g), vps-t-em (subgroup h), and vps-t-expp (subgroup i).

DISCUSSION

Three-dimensional analysis is based on the comparison of digital data (e.g., duplicate dies) to a master form. Computer-aided alignment of measurement data and master form allows for overcoming limitations

of the method described by Yamashita *et al.*⁵⁴⁾. As the experimental set-up used for this study had been developed in 1999 by Luthardt and was used ever since in his research group, it could be regarded as established. A variation of the set-up has been successfully used for the analysis of changes in gypsum dies over time⁹⁾.

As the set-up always includes gypsum expansion and digitizing error, a high-precision resin-modified, class 4 gypsum as well as a high-precision digitizing system with a low measurement uncertainty had to be used. Following the originally developed standard operation procedure, data sets were reduced to an even measurement point distance of 50 μm in order to reduce any influence of a differing data density on the results. This procedure also allows for a comparison of data gathered with different digitalization systems that have an unequal resolution. As always the same digitalization system was used in the study presented here, the influence of the data density is circumstantial. The data reduction also shortened the calculation time, which was an important factor a decade ago due to the performance of the computers used at that time. As even common personal computers nowadays are suitable for running the 3D analysis software and calculating results in a reasonably short time, one could argue that this step is not necessary any longer for study designs involving only a single digitizing system.

The precision of the data alignment before analysis, which was determined by the calculation of the RMS-error, is also of crucial significance for the systematic error. The precision of the alignment is in accordance with or even lower than previously reported^{8,55,56)}. The RMS-error always combines the systematic error of the experimental setup including the measurement uncertainty of the digitizing system used and the deviations between duplicate die and master CAD-model themselves. For the RMS-error, all positive and negative values are first squared, then the mean is calculated and finally the root is extracted thus preventing positive and negative values to neutralize each other. In this study, a RMS-error of 8 μm represents a series of dies without noteworthy deviations to the CAD-model or deviations within the systematic error of the experimental setup. Accordingly, 3D differences below $\pm 8\ \mu\text{m}$ cannot be detected using the presented method. A high RMS-error suggests larger deviations, given the fact that there is a low systematic error. A high RMS-error in combination with a high standard deviation is a sign for considerable variation between groups of dies made with the same impressions technique, as is the case for the two-phase putty and wash data presented here.

While, in theory, mechanical digitizing systems show a lower measurement uncertainty, such systems have limitations where free form surfaces are to be measured. Free form surfaces are surfaces with complex geometry such as prepared teeth. Thus, the systematic error cannot be lowered by using a mechanical digitizing system^{13,36)}. An alternative to high-precision optical digitizing systems could be the use of $\mu\text{-CT}$ ⁷⁾. The access to such systems is generally limited and investment

costs would be comparatively high.

The three-dimensional analysis of the deviations between the virtual CAD-model, which is the digital representation of the steel master model, and the digital data of the gypsum dies renders the maximum positive, maximum negative, mean positive, and mean negative deviations between each gypsum die and the steel master model. Using the CAD software, the distance between every single of the above mentioned approximately 23,500 measuring points per gypsum die and the CAD-model can be calculated. Due to the small distance of 50 μm between these points, the free-form shape of the prepared die (its surface) is fully described. The reduction to single linear two-dimensional measurements between predefined corresponding measuring points and the immanent loss of 3D information can thus be overcome. Also, there is no need for a shape restriction when free-form surfaces can be analyzed just as well as clearly geometrically defined shapes such as cones or cylinders. The assessment of many different experimental set-ups close to the dental clinical setting hence becomes possible^{2-4,8,37,45-47,49,57,58}.

Based on the experience from former *in vitro* and *in vivo* studies^{3,9,45-48,53,57}, maximum positive and negative deviations, which are also calculated by the CAD software, were not further evaluated. These values are usually the result of single or very few outlier points and are of little informative value. Positive and negative deviations of the duplicate dies from the virtual CAD-model can be evaluated only in relation to the latter. Positive values represent a duplicate die which is enlarged in circumference and/or height while negative values show a reduced circumference or shortening in relation to the master CAD-model. If there is only an enlargement found in all areas of the die (circumference, edges and height), negative values will be a result of the measuring uncertainty of the digitizing system used and will thus show values only equal to or below this magnitude. In contrary, negative deviations above the measuring uncertainty of the digitizing system indicate a reduction of circumference and/or height as well as a rounding of edges. These values must be reported separately in order to clearly differentiate between enlargement and reduction. In a combined presentation of both, positive and negative values, this could be a major confounder of the results. For example a die being clearly reduced in height and somewhat enlarged in circumference will show close to none deviation in the quantitative evaluation, if positive and negative values were combined.

In a study on the influence of laboratory surfactant by Tredwin *et al.*, different type 4 dental stones and impression materials were used than in the study at hand³³. However, a possible negative influence of a laboratory surfactant on the achievable precision could not be ruled out. For this reason, the use of surfactant was discarded. Using the wire rests and the stand prevented the materials from being distorted by the steel master model, especially during the critical phase towards the end of setting.

Fig. 5 Mean positive and negative deviations of the duplicate dies to the virtual master model (two-stage putty and wash technique (t)). Benchmark was set to ± 0.02 mm. Note the different scale of the y-axis compared with Fig. 4: ± 0.08 mm (± 80 μm) instead of ± 0.03 mm (± 30 μm). Outlier values are more than 1.5 times the box width away from the boxes' outer boundaries and are indicated by circles. Boxes with different letters are significantly different from one another, while those indexed with the same letter do not show any significant difference.

While summing up the positive and negative mean deviations found by the quantitative evaluation and presenting them in box-and-whisker plots (Figs. 4 and 5) is especially convenient for a benchmarking of many different impression techniques and materials, the complete information can only be encompassed, if in addition to the quantitative analysis the qualitative information on the distribution of deviations over the die surface (Figs. 2 and 3) is taken into consideration. The combination of these results is one of the major advantages of this experimental procedure. Based on previous studies, 3D mean deviations of ± 0.02 mm for

in vitro conditions and ± 0.04 to 0.05 mm in clinical sites are to be expected for high-precision final impression materials and techniques^{27,47,53,58}.

The qualitative analysis (Figs. 2 and 3) shows the distribution of deviations on the prepared tooth's surface. For monophasic and one-stage two-phase final impressions, a circumferential enlargement and a rounding of edges has shown to be typical, independently of the impression material and combination used. In contrast, the circumference of dies resulting from two-phase putty and wash impressions is reduced. Repositioning the tray with putty and wash material causes a certain distortion, which cannot be compensated by the material's ability for elastic recovery. This effect can be reduced depending on the flow and viscosity of the wash material²⁸, which would give an explanation for the two materials with comparably smaller deviations despite the impression technique used (vps-t-hon and vps-t-pan).

Comparing the materials for diagnostic cast impressions (Fig. 3), hand- and machine-mixed irreversible hydrocolloid show a distribution of deviations similar to final impression materials (techniques m and o). This high precision was also found in a 3D analysis by Chandran *et al.*³⁶. Machine-mixing induced fewer and smaller bubbles and thus resulted in a better surface quality of the gypsum die. The vps-based material showed a distinct circumferential reduction in size, which could cause problems, if the impression itself or the resulting gypsum model was used for making provisional restorations or mouth guards, as examples.

Although statistically significantly different, the small range of mean values of ± 7 – 8 μm between most subgroups, especially within the one-stage two-phase impression materials, suggests a minor clinical relevance. The largest differences were found within the group of materials used for the two-stage putty and wash technique, which is in line with results achieved by Fenske²³. The use of a die spacer for impressions rendering a reduced circumference is recommendable. Information on whether or not to use a die spacer has to be transmitted to the dental laboratory to achieve high precision.

The impression technique was shown to have a major influence on the achievable precision of duplicate dies independent of the composition of the materials used.

CONCLUSION

Three-dimensional analysis can give a complete picture of the precision of gypsum duplicate dies depending on the impression materials and impression techniques used. The visualization provides a detailed insight into occurring deviations in comparison to conventional *in vitro* analyses.

Processing aspects (manually or auto-mixing) and impression technique significantly influence the die precision. Independent of the materials used, very good 3D representation of the master die was found for the one-stage two-phase impression technique. However,

using the two-stage putty and wash technique, only two out of six addition-curing vinyl polysiloxanes showed comparably good results.

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