Qualitative and quantitative three-dimensional accuracy of a single tooth captured by elastomeric impression materials: An in vitro study

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Statement of problem. The accuracy of impressions has been described in 1 or 2 dimensions, whereas it is most desirable to evaluate the accuracy of impressions spatially, in 3 dimensions.

Purpose. The purpose of this study was to demonstrate the accuracy and reproducibility of a 3-dimensional (3-D) approach to assessing impression preciseness and to quantitatively comparing the occlusal correctness of gypsum dies made with different impression materials.

Material and methods. By using an aluminum replica of a maxillary molar, single-step dual viscosity impressions were made with 1 polyether/vinyl polysiloxane hybrid material (Identium), 1 vinyl polysiloxane (Panasil), and 1 polyether (Impregum) (n=5). Corresponding dies were made of Type IV gypsum and were optically digitized and aligned to the virtual reference of the aluminum tooth. Accuracy was analyzed by computing mean quadratic deviations between the virtual reference and the gypsum dies, while deviations of the dies among one another determined the reproducibility of the method. The virtual reference was adapted to create 15 occlusal contact points. The percentage of contact points deviating within a ±10μm tolerance limit (PDP_{10} = Percentage of Deviating Points within ±10μm Tolerance) was set as the index for assessing occlusal accuracy. Visual results for the difference from the reference tooth were displayed with colors, whereas mean deviation values as well as mean PDP_{10} differences were analyzed with a 1-way ANOVA and Scheffé post hoc comparisons (α=.05).

Results. Objective characterization of accuracy showed smooth axial surfaces to be undersized, whereas occlusal surfaces were accurate or enlarged when compared to the original tooth. The accuracy of the gypsum replicas ranged between 3 and 6 μm, while reproducibility results varied from 2 to 4 μm. Mean (SD) PDP_{10}-values were: Panasil 91% (±11), Identium 77% (±4) and Impregum 29% (±3). One-way ANOVA detected significant differences among the subjected impression materials (P<.001).

Conclusions. The accuracy and reproducibility of impressions were determined by 3-D analysis. Results were presented as color images and the newly developed PDP_{10}-index was successfully used to quantify spatial dimensions for complex occlusal anatomy. Impression materials with high PDP_{10}-values were shown to reproduce occlusal dimensions the most accurately. (J Prosthet Dent 2012;108:165-172)

Clinical Implications

Hybrid polyether/vinyl polysiloxane materials, vinyl polysiloxanes, and polyethers reproduce spatial dimensions with high accuracy and reproducibility. However, impression materials with high PDP^{10}-values might result in more accurate mounted casts.

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Dental impression materials have been subjected to a wide range of clinical trials and in vitro studies, in which various accuracy-influencing parameters such as material and tray selection,[1-9] rheological properties,[10,11] impression technique,[12-14] or position and curvature of preparation finish lines[15,16] were investigated. Physiochemical properties such as wetting behavior,[17,18] moisture displacement capability,[15,19] or flow under pressure[20] have also been investigated as important characteristics.

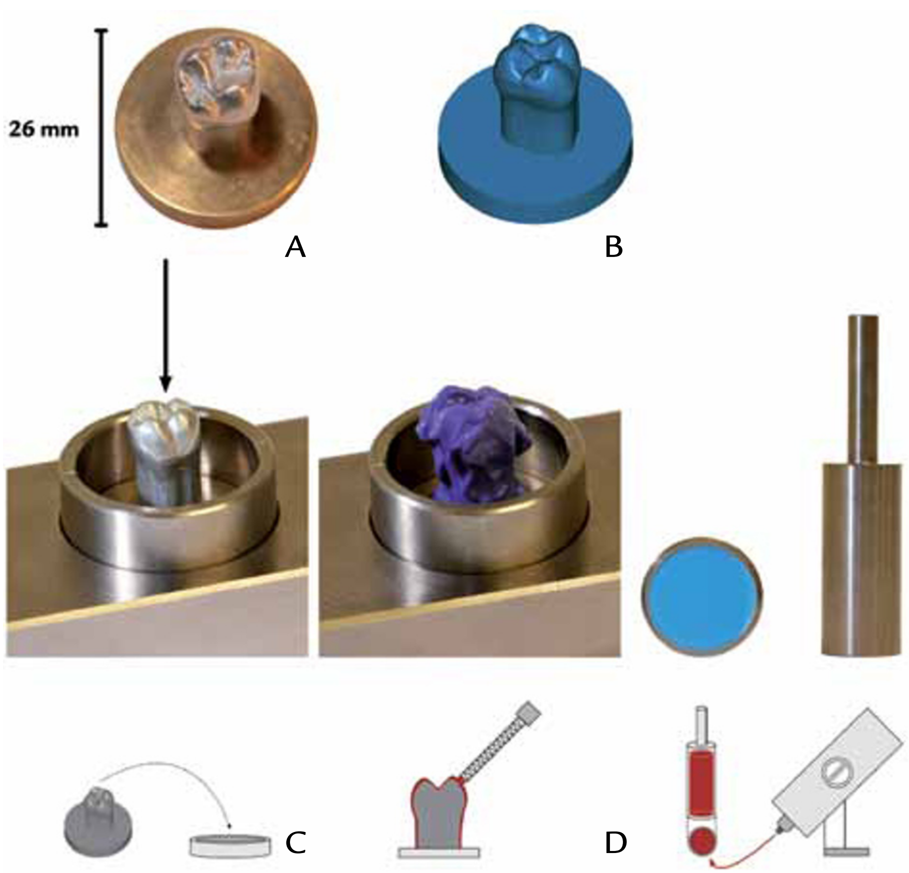
There is a broad range of elastomeric impression materials, the most popular of which are vinyl polysiloxanes (VPS), polyethers (PE) and polyether/vinyl polysiloxane hybrids (PE/VPS-hybrids). Although these materials experience complex 3-dimensional (3-D) changes during their polymerization and setting processes,[21-24] a sufficient index for quantifying 3-D deviations has not been established.

A newly introduced procedure allows the visualization of dimensional variations during impression-making as well as the 3-D quantification of spatial deviations with a single index. The objective of this in vitro study was to quantify and compare the spatial dimensions of gypsum replica dies formed from different impression materials. The null hypothesis was that there would be no significant differences in the spatial accuracy of the occlusal surface of a standard molar among the tested impression materials.

MATERIAL AND METHODS

The accuracy of 3 generic types of impression materials was assessed by means of computer-aided, 3-D analysis. An aluminum maxillary first molar with morphologically contoured cups and fissures served as the reference tooth (KaVo Dental GmbH, Biberach, Germany) along with its corresponding virtual representation (Fig. 1A, 1B). Three impression material combinations suitable for single step dual viscosity impressions were examined (Table I). Light-bodied impression materials were automixed with a hand-dispenser-system (Applyfix 4; Kettenbach GmbH, Eschenburg, Germany). Heavy-bodied impression materials were mixed and dispensed from a dynamic mixer (Sympress 6000; Renfert GmbH, Hilzingen, Germany) which achieves a homogenous quality with improved surface characteristics when compared to hand mixing.[26] All impressions were made at room temperature by a single investigator. An a-priori power analysis was conducted with a 3-group design, an assumed effect size of 1.25 and, an alpha level of .05. Single-sided testing revealed a power level of .95 at a total sample size of 15 (5 specimens per group). Moldovan et al[27] used similar sample sizes and means of evaluation for a novel computer-aided and 3-dimensional analysis of internal fit of zirconia copings in vitro.

The experimental design featured a rectangular base with a circular ring,

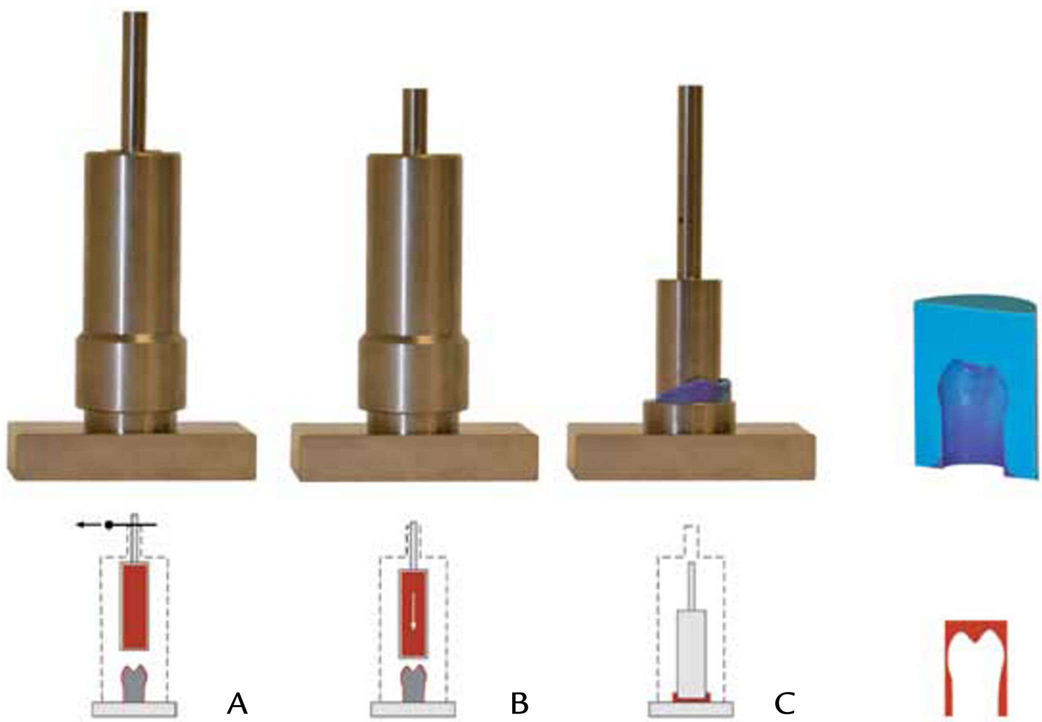


1 Experimental procedure used for standardized impression-making. Aluminum reference tooth (A) - actual, (B) - virtual data, was fitted into circular ring (C) and covered by light-bodied impression material (D). Simultaneously cylinder was loaded with heavy-bodied impression material, dispersed from automatic mixing device (E).

Table I. Evaluated impression systems

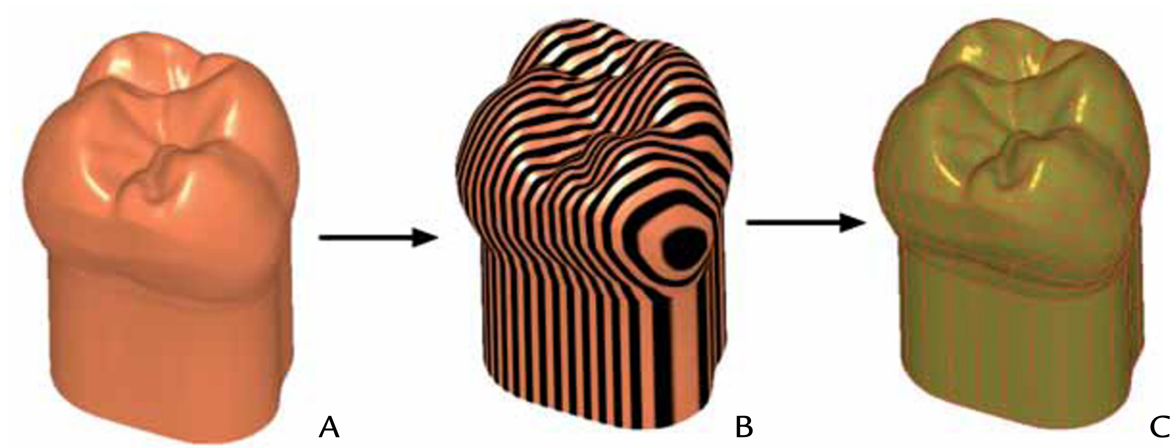
Token	Impression System	Chemical Composition	Manufacturer	Light-Body Material/ ISO 4823 Type[25]	Heavy-Body Material/ ISO 4823 Type[25]	Working/Setting Time (seconds)	Batch Numbers
IDE	Identium	VSE*	Kettenbach GmbH	Light/3	Heavy/1	120/210	90041/100091-19
PAN	Panasil	VPS	Kettenbach GmbH	Initial Contact Light/3	Tray Soft Heavy/1	90/150	100191/100921-74
IMP	Impregum	PE	3M Espe AG	Garant L DuoSoft/3	Penta H DuoSoft/1	120/210	409353/368082

VSE: Vinyl siloxane ether, VPS: vinyl polysiloxane, PE: polyether
* VSE is further referred to as polyether/vinyl polysiloxane hybrid (PE/VPS-hybrid)

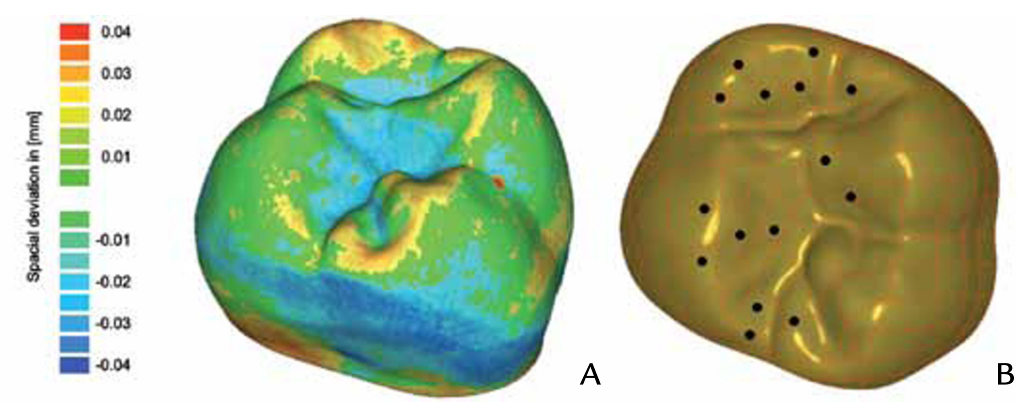


2 Impression-making procedure. Impression tray consisted of 2 concentric cylinders placed vertically above original tooth (A). Impressions were made as inner cylinder was lowered into seating position (B). Gap between inner and outer cylinder allowed free escape of excess impression material (C). After prolonged polymerization time, impressions were separated from reference tooth and finally inspected (D, impression was sectioned for illustration only).

into which the reference tooth was securely fastened (Fig. 1C). A hollow cylinder (Fig. 1E) simulated a stock tray, which was lowered over the reference tooth during impression making. Light-bodied impression material was injected on and around the reference tooth and then dispersed with syringe air for approximately 3 seconds (Fig. 1D). Filled with heavy-bodied impression material (Fig. 1E), the cylinder was placed vertically above the aluminum tooth and locked in this position (Fig. 2A). Within the appropriate working time, the cylinder was unlocked and gently lowered into the seating position with no additional force (Fig. 2B). As the hollow cylinder had a smaller diameter than the circular ring that secured the aluminum reference any excess impression material was allowed to escape freely via the resulting gap (Fig. 2C). For adequate polymerization at room temperature, the impressions were allowed to set 3 times longer than recommended by the manufacturer.[28] A minimum material thickness of 3 mm around the reference tooth minimized distortion once the impression was separated.[29,30] After removal from the reference (Fig. 2D), all impressions were inspected for defects by using ×2.7 magnification (starVision SV1; starMed GbR, Munich, Germany). Five impressions were made for each material combination. Thereafter, corresponding gypsum dies were formed with Type IV die stone (Silky Rock; Whip Mix, Louisville, Ky), which was suitable for optical digitalization in terms of both color (violet) and minimal expansion (0.09%). The recommended ratio of 23mL of distilled water to 100 g of powder was vacuum mixed (Wamix-Classic; Wassermann Dental-Maschinen GmbH, Hamburg, Germany), then slowly vibrated (KV-16; Wassermann Dental-Maschinen GmbH) into the impressions and allowed to set for 45 minutes before removal and final inspection. Before die formation, the vinyl polysiloxane impressions were treated with a sur-



3 Digitalization procedure. Impressions were poured with Type IV die stone (A) and optically digitized with structured-light scanner. Distortions of projected light bands (B) allowed calculation of 3-D data points (x, y, z) representing object's surface. Virtual datasets of digitalized gypsum duplicates were saved in STL format (C).



4 Qualitative and quantitative deviation analysis. Color-coded difference image (A) consisting of 19 colored segments. Blue shades indicate negative deviations (smaller duplicate die), whereas yellow to red shades point out positive deviations (larger duplicate die). PDP[10]-calculation requires extended virtual reference model. Fifteen occlusal contact points were added following tripodization criteria according to Payne and Lundeen36 (B).

factant (Debubblizer Surfactant; Almore Intl Inc, Portland, Ore) to reduce surface tension and improve the quality of the resulting cast.[31-34] Therefore, a consistent amount of surfactant (3 spray bursts, approximately 0.5 mL) was dispersed into the impression negatives and remained there for 30 seconds. Syringe air was used to remove the excessive surfactant and gently dry the impression's surfaces.

The gypsum dies (Fig. 3A) were then digitized with a structure light scanner (kolibri Flex 20; IVB GmbH, Jena, Germany). Single light bands were projected onto the gypsum surface (Fig. 3B) and simultaneously recorded with 3 high-resolution camera lenses mounted one to another at a predefined angle (triangulation angle). Triangulation routines allowed calculation of data points from the captured images that could be displayed in a common coordinate system. Three data points were combined to form triangles over the entire surface, resulting in an accurate virtual representation of the digitalized object. Data sets for each gypsum specimen were computed and saved in an STL format (Fig. 3C). STL records of reference and duplicate teeth were superimposed one on the other by calculating all possible occlusal orientations and selecting the one with the best object-to-object penetration (so called Best-Fit-Method).[23]

Dimensional differences were computed and qualitatively analyzed by color-coded difference images (Fig. 4A). For basic quantitative analysis, the mean quadratic deviation (root mean square, RMS)[23] of all measuring points was calculated by the following formula:
$x_{1,i}$: measuring point i on reference,
$x_{2,i}$: measuring point i on duplicate
n : total number of measuring points

$$RMS=\sqrt{\frac{\sum_{i=1}^{n}(z_{1,i}-x_{2,i})^2}{n}}$$

RMS can serve as a measure of how far deviations between 2 different datasets vary from zero.[35] In the present study, low RMS-scores indicate high 3-D congruency of 2 superimposed records. The RMS between virtual reference and duplicates accounts for overall accuracy, while the RMS of the duplicates among one another measures the reproducibility of the method.

For further quantification, the occlusal surface of the virtual reference tooth was adapted by adding 15 tripod occlusal contact points as shown in Figure 4B, according to the added wax technique described by Payne and Lundeen.[36] The software package (Geomagic Qualify 11; Geomagic GmbH, Stuttgart, Germany) allows the user to specify so called "geometrical features." In this context a "feature" means a regular geometrical shape of interest that can be found within the virtual surface. Therefore, occlusal contact points were added as spherical contours with a total contact area <1 mm^2 and a preset tolerance of ±10 μm. Once a virtual duplicate was aligned to the reference, the software analyzed all geometrical features of interest (contact points) with respect to the defined tolerances. The percentage of data points within the contact area that deviate within a ±10 μm tolerance limit (PDP_{10}) was defined as an index for spatial accuracy. High percentage PDP_{10}-values denote high 3-D accuracy of the occlusal contact area.

One-way analysis of variance (ANOVA) was conducted for the 3 impression material systems, with RMS-values for accuracy and reproducibility as well as PDP_{10}-scores being dependent variables (PASW Statistics 18; SPSS Inc, Chicago, Ill). Saphiro-Wilk's test for normality and Levene's test for equality of variances were performed. Scheffé's conservative post hoc method was applied to detect significant differences among means (α=.05).

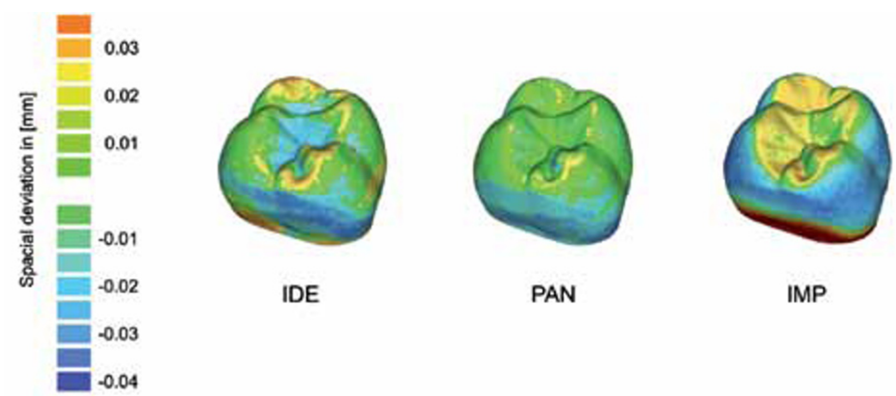
RESULTS

The IDE material (Fig. 5A) showed oversized dimensions in areas with strong curvatures (buccal and lingual smooth surfaces, occlusal ridges), whereas the mesial and distal surfaces were relatively undersized. Cervical regions were enlarged.

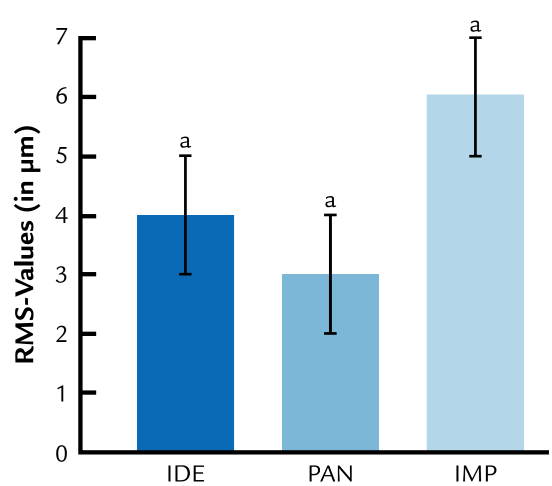
PAN (Fig. 5B) featured dimensional correctness consistently distributed along the occlusal surface. The palatal and vestibular slopes of both the centric and noncentric cusps were reproduced in exact agreement with the reference cast. Mesial, distal, and cervical areas showed decreased dimensions.

The polyether IMP (Fig. 5C) featured an enlarged occlusal surface with isolated areas of correct dimension (central ridges and bulges). The upper half of the circumferential region was undersized with a substantially enlarged cervical portion.

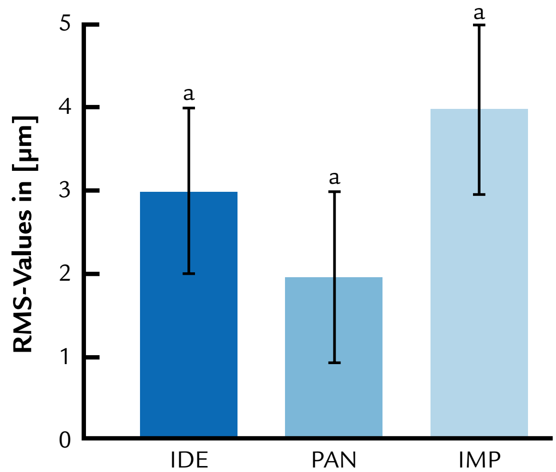
The results for basic deviation analysis (RMS-values) are shown in Figures 6 and 7. The accuracy of the gypsum replicas ranged between 3 and 6 μm, while reproducibility varied from 2 to 4 μm. ANOVA showed no statistically significant differences for both accuracy and reproducibility. The results for occlusal deviation analysis (PDP_{10}-values) are shown in Figure 8. Mean (SD) PDP_{10}-values were: PAN 91% (±11), IDE 77% (±4) and IMP 29% (±3). The applied single-factor ANOVA showed statistically significant differences among the



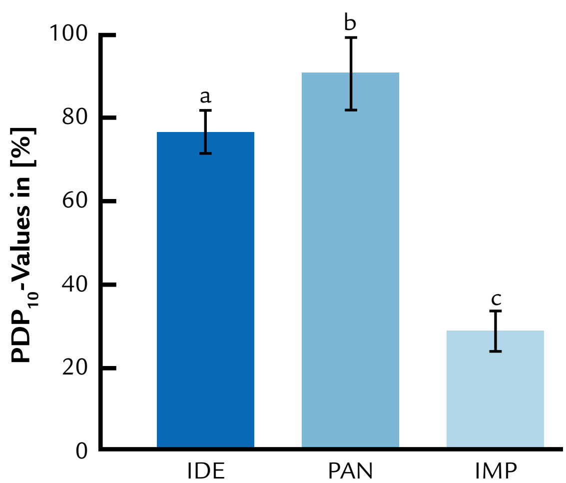
5 Color-coded difference images for quantitative deviation analysis. Gypsum replicas captured by different impression materials were compared to virtual reference. Overall, undersized smooth surfaces with slightly enlarged mesiodistal diameters and oversized cervical portions were found.



6 Mean RMS-values in [μm] of deviations between virtual reference and duplicate dies describing accuracy of measurement method (mean and standard deviation from n=5; groups with different lowercase letters indicate significant differences at P<.05). Differences were not statistically significant (P=.08).



7 Mean RMS-values in [µm] of deviations between the duplicate dies describing reproducibility of measurement method (mean and standard deviation from n=5; groups with different lowercase letters indicate significant differences at $P<.05$). Differences were not statistically significant ($P=.09$).



8 Mean PDP^{10}-values in [%] for quantitative deviation analysis among all evaluated impression materials (mean and standard deviation from n=5; groups with different lowercase letters indicate significant differences at $P<.05$). Differences were statistically significant ($P<.001$).

tested impression systems ($P<.001$). With Shapiro-Wilk's and Levene's test being non-significant, normality and equality assumptions were met.

DISCUSSION

The null hypothesis of this study, that there would be no significant differences in occlusal accuracy among the evaluated impression materials, was rejected because statistically significant differences emerged. Results for accuracy and reproducibility imply high trueness and precision of the presented method. However, the comparison to similar studies is difficult, since different digitalization systems and evaluation methods were used. Persson et al[24] reported deviations of a single die to range from 0.5 to 4.5 µm, depending on crown shape. Luthardt et al[23] compared the accuracy of digital and conventional impressions. When considering quadrants, elastomeric impression materials showed deviations of 19 µm. Ender et al[22] examined the accuracy and reproducibility of complete arch impressions, with an elastomeric impression material being as accurate as 55 µm.

To avoid occlusal interferences in centric relation occlusion or with mandibular excursions, accurate casts and their precise mounting is a prerequisite. Not only does this include the use of a facebow for correct positioning of the maxillary cast but also the ideal mutual orientation of the maxillary arch in relation to the mandibular cast. This requires impression materials that reproduce the occlusal surfaces with accuracy. As the PDP_{10}-index detects occlusal inaccuracies, impression materials with high PDP_{10}-scores might result in more accurate simulations of mounted casts.

Polymerization of elastomeric impression materials includes linkage of monomers to macromolecules associated with a substantial loss of spatial volume. Dimensional deviations are inherent to the elastomeric molecular structure and should be described in a 3-D manner. In general, 3-D procedures take the complex dental anatomy into consideration and, therefore, render more clinically relevant information than the previously used 1- or 2-dimensional approaches. Triangulation routines are known for inaccuracies during digitalization and feature system-related variations <0.1 µm.[37]

Excellent flow under pressure of light-bodied impression materials is clinically desirable, especially with subgingival preparation finish lines. In contrast, only a thixotropic material that remains "in place" once the tray is seated, promotes highly accurate reproductions of entire clinical crowns. Therefore, manufacturers should consider to balancing flow and thixotropic behavior because the long-term clinical success of partial fixed dental prostheses involves both marginal adaption to preparations and occlusal/functional correctness. From a clinical perspective, modified stock trays may help to increase overall accuracy of prepared and nonprepared teeth because they limit unintended flow, especially distally of the last captured tooth, while increasing the ram pressure needed for subgingival impression making.

Although the setting expansion of modern Type IV die stones is designed to match the inherent volume loss of elastomeric impression materials,[21] gypsum working casts were shown to be oversized when compared to the natural dentition.[28] Since technical improvements in 3-D imaging procedures enable a direct digitalization of impression negatives, the actual impact of gypsum casts on 3-D accuracy should be further examined.

The 3-D accuracy test of the entire crown established a basis for subsequent occlusal analyses. PAN featured accurate surface reproduction (Fig. 5B) and also showed the highest absolute PDP_{10}-values among the tested impression materials. Objectively IMP exhibited an oversized occlusal surface (Fig. 5C) connected with low PDP_{10}-scores. In fact, general trends that emerged qualitatively could be justified by PDP_{10}-data to some extent. However, the PDP_{10}-index only accounts for a small portion of the entire clinical crown, primarily focusing on functional aspects, while the objective characterization of accuracy considers the total anatomical shape.

This study has several limitations. Impressions were made of an idealized model of a first maxillary molar. The aluminum surface used differs from dentin and enamel in terms of surface structure, wettability, and hardness. The absence of any soft tissue, saliva, or sulcular fluid and the ambient temperature and humidity differ significantly from the oral situation. A standardized tray positioning without applying extra forces and a circular material thickness greater than 3 mm is clinically advisable,[29,30] yet not generally practicable. Finally, the PDP_{10}-analysis should be extended to the entire surface of a prepared tooth with emphasis on the finish line to add to the clinical usefulness of this approach.

CONCLUSIONS

Within the limitations of this study it was shown that all of the tested impression material systems achieve accurate and reproducible results. The viability of a spatial computer-aided accuracy analysis was demonstrated for an entire clinical crown of a maxillary molar. The PDP_{10}-index was successfully used to quantify spatial dimensions of complex occlusal shapes primarily focusing on functional aspects. Impression materials with high PDP_{10}-values were shown to reproduce occlusal dimensions the most accurately.

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NOTEWORTHY ABSTRACTS OF THE CURRENT LITERATURE

The future of dental devices is digital

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Objectives: Major changes are taking place in dental laboratories as a result of new digital technologies. Our aim is to provide an overview of these changes. In this article the reader will be introduced to the range of layered fabrication technologies and suggestions are made how these might be used in dentistry.

Methods: Key publications in English from the past two decades are surveyed.

Results: The first digital revolution took place many years ago now with the production of dental restorations such as veneers, inlays, crowns and bridges using dental CAD-CAM systems and new improved systems appear on the market with great rapidity. The reducing cost of processing power will ensure that these developments will continue as exemplified by the recent introduction of a new range of digital intra-oral scanners. With regard to the manufacture of prostheses this is currently dominated by subtractive machining technology but it is inevitable that the additive processing routes of layered fabrication, such as FDM, SLA, SLM and inkjet printing, will start to have an impact. In principle there is no reason why the technology cannot be extended to all aspects of production of dental prostheses and include customized implants, full denture construction and orthodontic appliances. In fact anything that you might expect a dental laboratory to produce can be done digitally and potentially more consistently, quicker and at a reduced cost.

Significance: Dental device manufacturing will experience a second revolution when layered fabrication techniques reach the point of being able to produce high quality dental prostheses. The challenge for the dental materials research community is to marry the technology with materials that are suitable for use in dentistry. This can potentially take dental materials research in a totally different direction.