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Accuracy of complete-arch dental impressions: a new method of measuring trueness and precision

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Abstract: STATEMENT OF PROBLEM: A new approach to both 3-dimensional (3D) trueness and precision is necessary to assess the accuracy of intraoral digital impressions and compare them to conventionally acquired impressions. PURPOSE: The purpose of this in vitro study was to evaluate whether a new reference scanner is capable of measuring conventional and digital intraoral complete-arch impressions for 3D accuracy. MATERIAL AND METHODS: A steel reference dentate model was fabricated and measured with a reference scanner (digital reference model). Conventional impressions were made from the reference model, poured with Type IV dental stone, scanned with the reference scanner, and exported as digital models. Additionally, digital impressions of the reference model were made and the digital models were exported. Precision was measured by superimposing the digital models within each group. Superimposing the digital models on the digital reference model assessed the trueness of each impression method. Statistical significance was assessed with an independent sample t test (=.05). RESULTS: The reference scanner delivered high accuracy over the entire dental arch with a precision of 1.6 ±0.6 µm and a trueness of 5.3 ±1.1 µm. Conventional impressions showed significantly higher precision (12.5 ±2.5 µm) and trueness values (20.4 ±2.2 µm) with small deviations in the second molar region (P<.001). Digital impressions were significantly less accurate with a precision of 32.4 ±9.6 µm and a trueness of 58.6 ±15.8µm (P<.001). More systematic deviations of the digital models were visible across the entire dental arch. CONCLUSIONS: The new reference scanner is capable of measuring the precision and trueness of both digital and conventional complete-arch impressions. The digital impression is less accurate and shows a different pattern of deviation than the conventional impression.

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Dental full arch impression, a new high accurate method of measuring trueness and precision

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Abstract

Objectives: With the digital intraoral impression a new class of impression techniques is introduced. To assess the accuracy of these impressions and compare it to conventional intraoral impression technique threedimensional trueness and precision measurements are necessary. The aim of this study was to evaluate wether a new reference scanner is capable to measure these threedimensional deviations occuring with conventional and digital intraoral impression techniques of full arch impressions of an in vitro model.

Methods: A steel reference model was scanned with the reference scanner to evaluate precision and trueness. The reference model then was used to perform five conventional impressions with a polyvinylsiloxanether material (Identium, Kettenbach) in a putty and wash technique with standard stock trays (ASA Permalock, ASA Dental). The conventional impressions were poured with Type IV stone (CamBase, Dentona) and scanned with the reference scanner. Five digital impressions with a optical intraoral scanning system (CEREC AC, Sirona) were made. In each group, the models were superimposed and the differences computed with a signed nearest neighbour method. The 90-10%/2 percentile of the differences from each comparison was taken to compute the mean value for precision. The trueness of each impression method was assessed through superimposition of the impressions with the refefence scan of the steel reference model.

Results: The reference scanner delivers an accuracy with 1.6±0.6 μm for precision and 5.3±1.1 μm for trueness over a full dental arch scan. The conventional impression method shows significant higher ($p<0.001$) precision (12.5±2.5 μm) and trueness (20.4±2.2 μm) with only little amount of larger deviations at the second molar region. The digital impression method was significantly less accurate ($p<0.001$) with a precision of 32.4±9.6 μm and trueness of 58.6±15.8 μm. More systematic deviation of the digital model is visible across the entire dental arch.

Significance:The new reference scanner is capable to measure precision and trueness of both conventional and digital full arch impressions. The digital intraoral impression is less accurate and shows a complete different pattern of deviation than the conventional impression method.

Introduction

Dental impressions are a major step in restorative dentistry. They transfer the intraoral situation of the preparation, the adjacent teeth, the soft tissue and the antagonist to an extraoral model. This model is then used to produce the final restoration.

The accuracy of this model influences the fit or the restorations which is a major factor for longevitiy of the restoration (Wettstein, Sailer, Roos, & Hammerle, 2008)(Perakis, Belser, & Magne, 2004)(Persson, ODEN, ANDERSSON, & Sandborgh-Englund, 2009).

Todays gold standard impression technique ist the physical impression with elastomeric impression material and stock trays (CI). This negative form of the patients teeth is then poured with stone, resulting in a physical gypsum model. Various techniques are described in literature in order to archieve most accurate results (Piwowarczyk, Ottl, Buchler, Lauer, & Hoffmann, 2002)(Chandran, D. Jagger, R. Jagger, & Barbour, 2010). With the development of CAD/CAM systems and especially the use of zirkoniumdioxid for dental restorations, the digital model becomes more and more important. Parts of the gypsum model, at least the preparation, had to be digitized with an extraoral scanner to create a digital threedimensional model. On this digital model, the restoration is designed on a computer with special design software and then milled out of a material block in a CNC milling machine (Luthardt, Sandkuhl, Herold, & Walter, 2001). After milling, the dental technician finishes the restoration at the gypsum model. The latest development in CAD/CAM dentistry is the digital intraoral impression (DI)(Fasbinder, 2010)(Beuer, Schweiger, & Edelhoff, 2008). The digital intraoral impression(DI) results in a threedimensional virtual model from scanning the patients teeth directly inside the mouth. Construction and milling can be carried out without a conventional intraoral impression (CI) with the gypsum model and the following extraoral digitization. If needed, a physical model can be by rapid prototyping (SLA, 3D-printing or miling) from the intraoral digital impression data (Fasbinder, 2010).

A fundamental question, beside the clinical handling of the devices for the digital intraoral impression (DI) and the ease of the following steps in the digital workflow, is the accuracy of this new impression technique.

Accuracy consists of precision and trueness (ISO 5725-1). Precision describes, how close repeated measurements are to each other. The higher the precision, the more predictable is the measurement. Trueness describes, how far the measurement is from the real value of the measured object. A high trueness delivers a result that is close or equal to the real value of the measured object.

Precision measurements compare the results of repeated measurements with a specific impression method LIT)). Trueness measurement for conventional intraoral impression with gypsum models are most frequently linear distance measurements (Chandran et al., 2010)(Wostmann, Rehmann, & Balkenhol, 2009)(Hoyos & Soderholm, 2011). This method is restricted to few measuring points, the need of specific geometric points with clear markers for the measurement and the lack of displaying threedimensional changes of the dental model like torsions and axis deviations (Chandran et al., 2010)(Brosky, Pesun, Lowder, Delong, & Hodges, 2002)(Caputi & Varvara, 2008).

Threedimensional examination of trueness of impressions and gypsum models are rare in literature. A demand is to know the real surface of the testing object. Therefore the need of a reference scanner or the accessibility of a well known reference model to measure the real surface of the testing object, e.g. the tooth or the dental arch, is the limiting issue. It is possible to measure surfaces points with high trueness with CMM machines. But these methods are lacking scan speed and the restriction of measuring freeform surfaces like fissure lines and interproximal areas because of the geometrical size of the tipball (Quaas, Rudolph, & Luthardt, 2007)(Delong, Heinzen, Hodges, Ko, & Douglas, 2003). Optical scanners with high accuracy are currently limited to small measurement fields like single teeth or quadrants (Luthardt, Kuhmstedt, & Walter, 2003)(Mehl, Ender, Mörmann, & Attin, 2009). Another method for accessing trueness of a scanner is scanning calibrated objects like a sphere or material block of known size or diameter (Vlaar & van der Zel, 2006)(Delong et al., 2003). These calibrated objects are very small and do not have the typical morphology of teeth or the dental arch.

The aim of this study was

(1) to evaluate a new scanner with a specific scanning method to access high precise and true surface scans of full arch models and

(2) verify, if the accuracy of this scanner is high enough to describe deviations from conventional and digital impressions.

Materials and methods:

A metal model (Wirobond plus, Bego, Germany) of a patients upper dental arch was made. Two full crown preparations (second premolar and second molar ind the second quadrant) and one inlay preparation (first premolar in the first quadrant) were performed

(Image 1). This reference model was the base for all further conventional and digital impressions.

1. Accuracy evaluation of the reference scanner, (a) precision and (b) trueness

(a) The reference model was scanned with a slightly reference scanner (InfiniteFocus Standard, Alicona Imaging, Graz, Austria) five times in the same x-y-z direction with the optimal scan settings for the model material. A 5x magnification objective was used. The point size was 1,6x1,6μm in X-Y direction and 0.25μm in Z-direction. For the most accurate scanning results, a horizontal base around the teeth is necessary (Image1), that is scanned together with the tooth surface. Scan time for a full arch model was 18 to 29 hours. After scanning, the base is trimmed with the „3D editor" software module inside the IFM Software. The trimmed scan results in a data set of about 20 million surface points (image 2). The five data sets were superimposed with the difference analysis software (IFM software 3.5.0.1, Alicona Imaging, Graz, Austria) with a best fit algorithm. The software computes the difference from each measuring point of one scan to the next neighbour point of the second scan. A difference image of the two superimposed scans is created (image 3) and saved as an image for visual analysis of deviations. The signed nearest neighbour distances of each surface point between scan 1 and scan 2 are saved. This file is exported to Microsoft Excel (Excel:mac 2011, Microsoft, Unterschleissheim, Germany) and the 90-10%/2 percentile is computed. This value represents the range where 80 percent of all differences between the two superimposed scans are placed. The average of all 90-

10%/2 percentiles is taken as the result for precision of the reference scanner and displayed in table 1.

(b) The reference model was scanned additionally four times in a rotated position of about 90 degress around the z axis and 10 to 20 degrees in x-y axis. These scans were compared to the first non rotated scan in the same manner. The results of these comparisons are displayed in table 2. The rotated scans reveal any filter effects, calibrating errors and matching errors of the software and are the validation of the trueness of the scanner.

2. Accuracy of conventional impression material and gypsum model fabrication

Five conventional impressions were taken with a vinysiloxanether impression material (Identium, Kettenbach, Eschenburg, Germany) and metal stock trays (ASA Perma-Lock, ASA Dental, Bozzano, Italien) in a putty and wash technipue. The impression material was set for 10 min on the model and then the impression removed from front to back of the model. After eight hours the impression was poured with type IV gypsum (Cam-Base, Dentona AG, Dortmund, Deutschland) and set in upright position to harden. After 40 min, the models were removed from the impression and stored for 24 to 48 hours at room temperature before scanning with the reference scanner. The models were scanned with the reference scanner (IFM 3.5.0.1, Alicona Imaging, Graz, Austria) with the occlusal surface oriented horizontal at the centre of the y-x table and again with the horizontal base around the dental arch. The measure point size was 1.6μmx1.6μm in x-y direction and 0.25μm z-direction. After trimming the horizontal base, each scan resulted in a three-dimensional model with about 20 million measured surface points.

(a) The model scans were compared to each other to aquire the value for precision of the conventional impression and

(b) compared to the scan of the reference model to determine the trueness of the conventional impression method.

The difference analysis was performed in the same way as described in number 1(a).

3. Accuracy of digital impressions

Five digital impressions of the reference model were taken with the CEREC AC System (Sirona Dental Company, Bensheim, Germany) using the CEREC Connect Software 3.82. The reference model was matted with OptiSpray (Sirona Dental Systems, Bensheim, Germany) and scanned with around 20 optical impressions to aquire the entire dental arch. The resulting model was exported tas an STL file and imported into the Alicona IFM Software for comparison to the reference model scanned with the Alicona IFM device.

(a) The digital impressions were superimposed to each other and the differences display the precision of the digital impression.

(b) The superimposition of the digital impressions with the reference model gives the basisfor the trueness of the digital impression method.

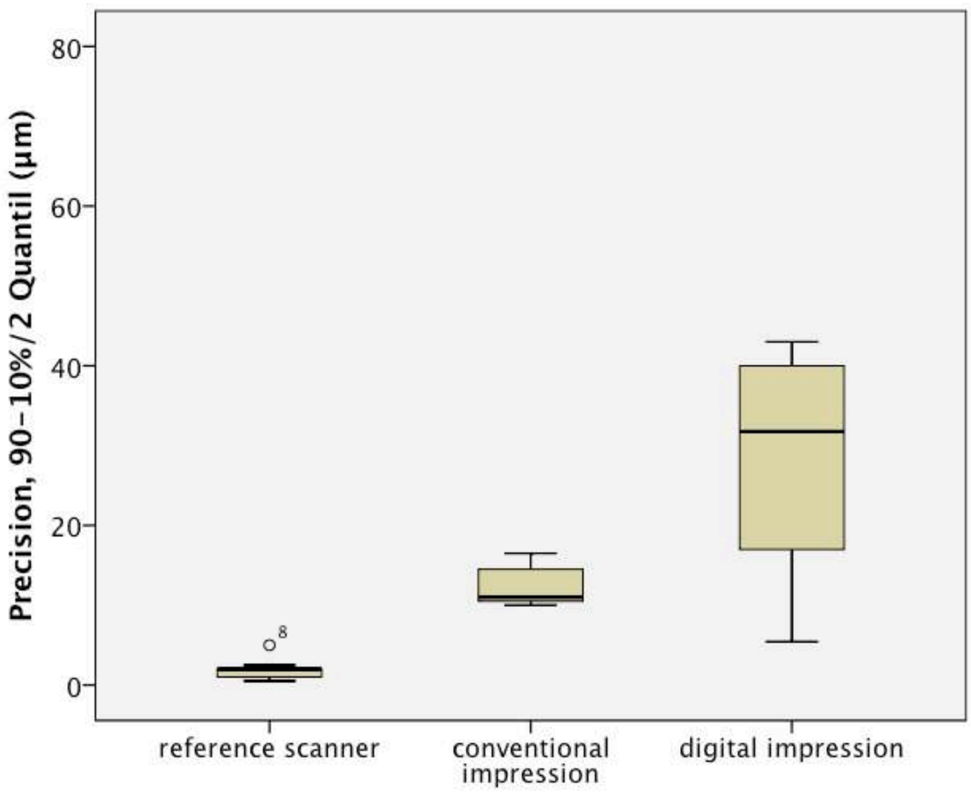
The difference analysis was performed in the same way as described in number 1(a).

The independent sample t-test was used to analyse statistical differences between the groups 1(a), 2(a) and 3(a) for the precision as well as 1(b), 2(b) and 3(b) for trueness of the different impression methods with $p<0.05$ (IBM SPSS Statistics Version 19, IBM SPSS, Chicag, USA).

Results

1. Accuracy evaluation of the reference scanner, (a) precision and (b) trueness

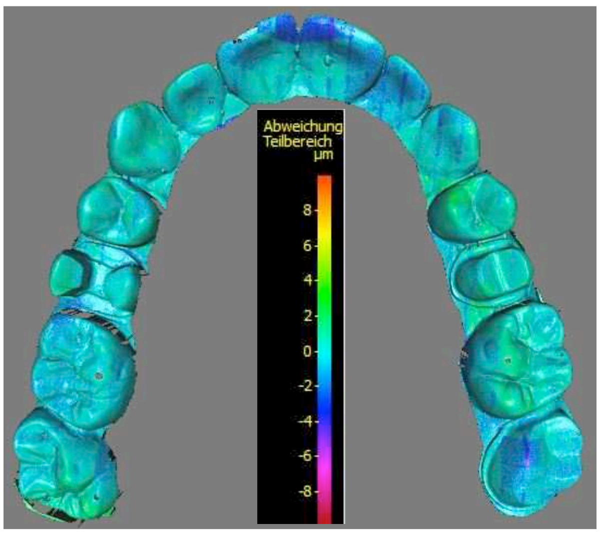
Image 4 shows the result of the precision measurement of the reference scanner. The 90-10% /2 quantil of all comparisons are located between ±0.5 and ± 2.5 with a mean



of 1.6±0.6 μm (median 2.0 μm) over the entire dental arch.

Image 4: boxplot of precision measurement

The difference images (image 5 a,b) show the coloured differences between two repeated scans in a range from -10μm to +10μm. A homogenous deviation over the entire dental arch with maximum values of 5μm on steep oral inclines of the incisor and the second molar is visible. The matching areas of the single images are visible in these special regions and show a higher deviatin than less angulated surfaces like the occlusal area of molars and incisal regions of the anteriors. This error occur on almost every scan and is addicted to the scanning process and image stitching routines. The error does not cumulate over larger areas but is only in these particular regions.



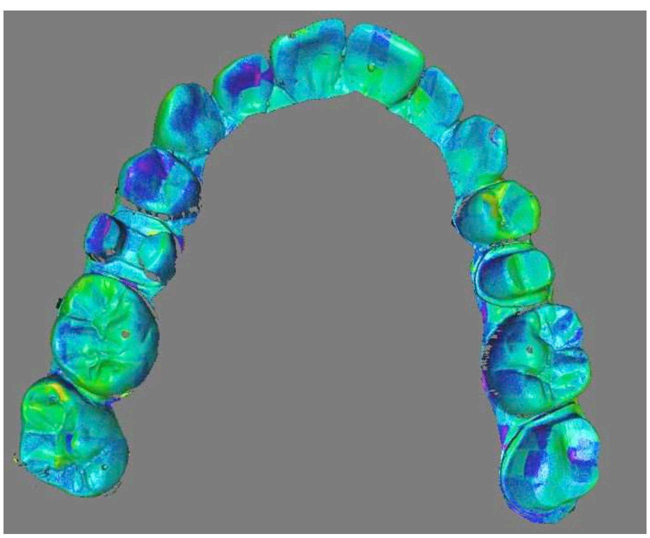
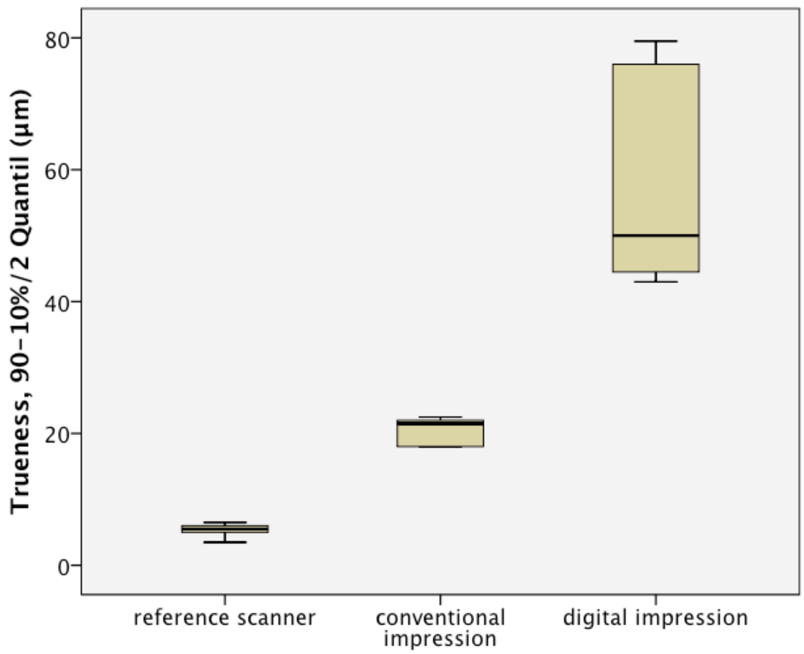


Image 5(a,b): Difference images of two repeated scans of the master model. The difference color map is set from -10μm to +10μm. A homogenous difference mapping of ±2μm is visible with local peaks to ±5μm

Image 6 shows the results of the trueness measurement of the reference scanner. The 90-10%/2 Quantil of all comparisons are located between ±3.5 to ±6.5 μm with a mean



of 5.3±1.1 μm (median 5.5 μm) over the entire dental arch.

Image 6: boxplot of trueness measurement

The difference images show the highest deviation in the second molar region of the first quadrant and on the oral flanks of the canine (Image 6a,b). Maximum deviations are about 8μm again in steep flanks of the tooth surface. The first quadrant shows a little compression of the first and second molar and the second quadrant reveals a slight vertical rotation of the dental arch from negativ deviations of the oral walls in the anterior to positiv deviations of the oral walls in the posterior region.

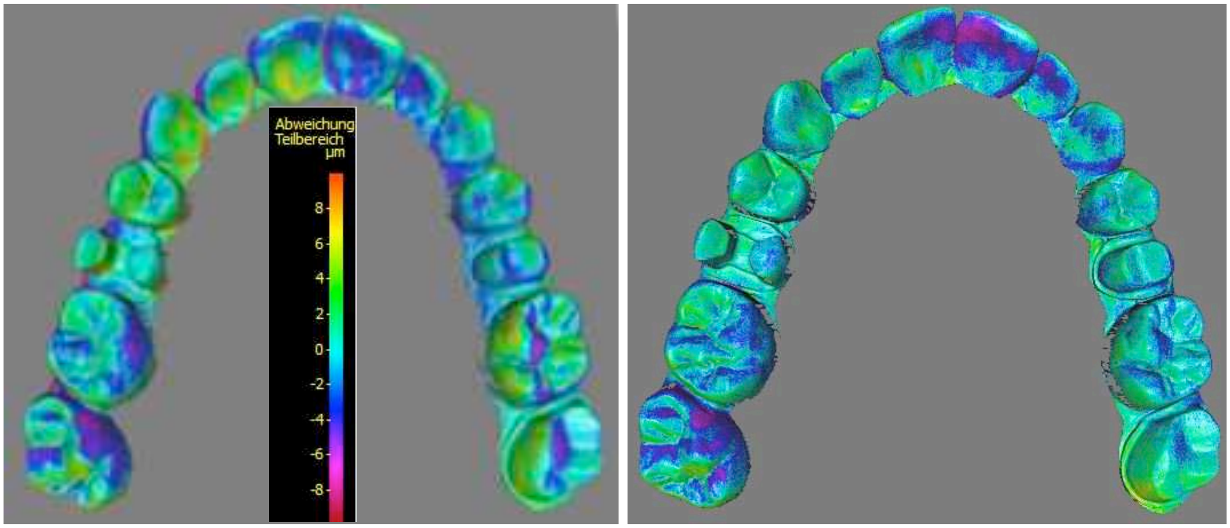


Image 7(a,b): Difference images of two rotated scans. The difference color map is set from -10μm to +10μm. Large areas differ up to 4μm while the steep flanks of the anteriors and second molars show some higher differences up to 10μm.

2. Accuracy of conventional impression and gypsum model

The test group of conventional impressions with gypsum model revealed a mean precision of 12.5±2.5 μm (median 11.0μm) (image 4). The mean deviation from the reference model is 20.4±2.2 μm (median 21.5μm) (trueness of the gypsum model) (image 6). The values of the single comparisons are close to another, showing a high reliability of the conventional impression in this in-vitro setup. The independent sample T-Test shows a highest significant difference to the values from the reference scanner (p<0.001).

The visual evaluation of the precision measurement show small deviations in the anterior and premolar regions of around 10μm and the higher and irregular occuring discrepancies of the second molar with maximum values up to 50μm (Image 7 a,b).

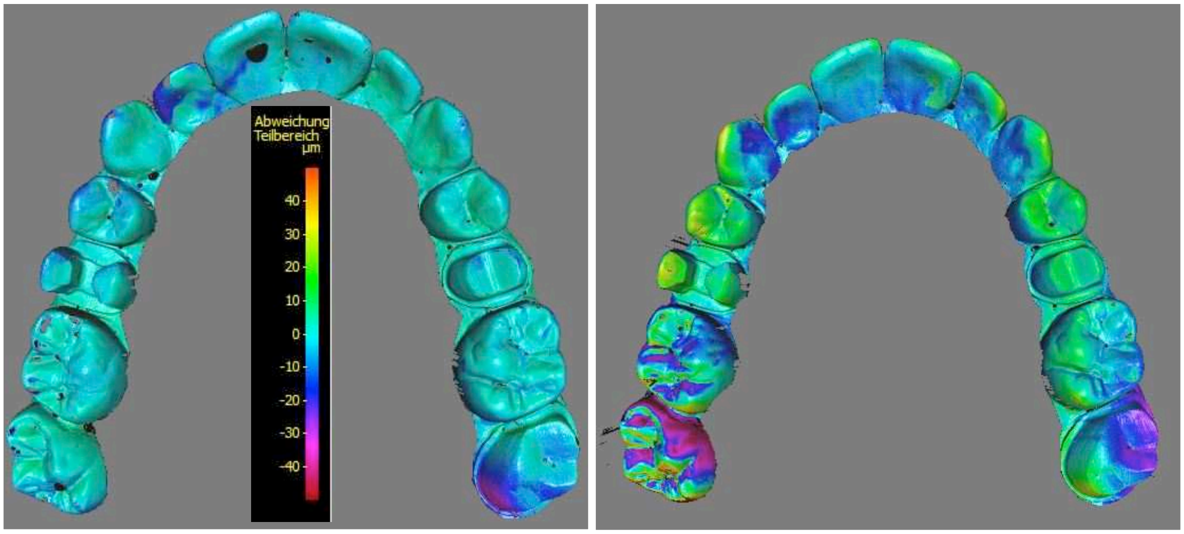


Image 8 a,b: Difference map of two repeated scans. The color difference map is set from -50μm to +50μm. While in the anterior region only little deviations up to 20μm occur, the distal end of the arch shows irregular deformations up to 50μm.

The visual examination of the difference images from the trueness show very low deviations in the anterior region from canine to canine. In the premolar and molar region, the deviations are higher and the gypsum model is slightly larger than the reference model. At the distal end of the dental arch, irregular deviations occur with the highest deviations of up to 50μm.

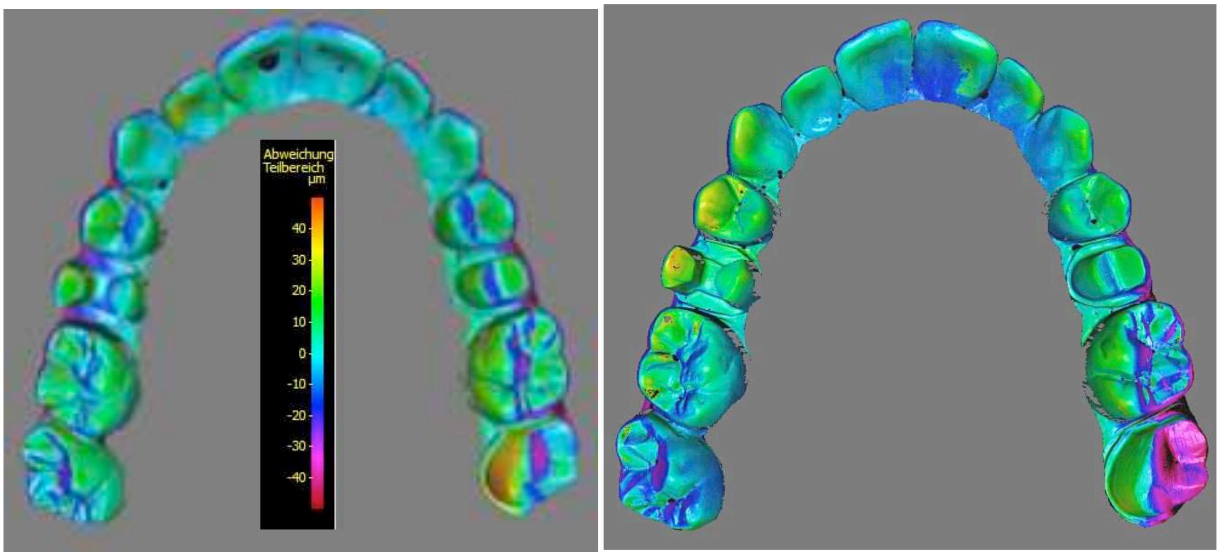


Image 9 a,b: Difference image of trueness measurement. The difference color map is set from -50 to +50µm. 9a shows that the gypsum model is slightly larger than the reference model with rising deviation to the distal end of the dental arch. 9b shows additional a distortion in the region of the second molar of the second quadrant.

3. Digital impression

The digital impression method with the CEREC Bluecam showed a precision of 32.4±9.6 µm (median 31.7µm). The differences of virtual from the reference model (trueness) are 58.6±15.8 µm (median 50µm). The independent sample T-Test shows highest significant differences to the values from the reference scanner and conventional impression group ($p<0.001$). The difference images (Image 10,11) show the coloured differences between -50µm and +50µm.

The differences of the precision images show irregular deviation pattern. The anterior region is more precise than the posterior and the higher posterior deviations are located only at one side of the model (image 10 a,b).

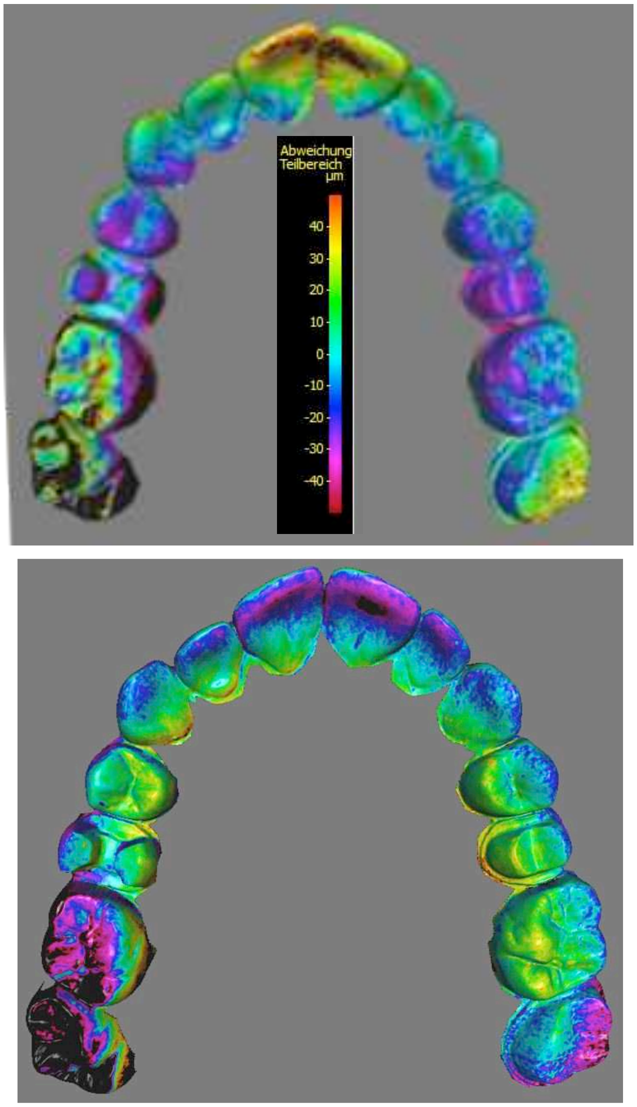


Image 10 a,b: Difference image of two repeated digital impressions. The color difference map is set from -50μm to +50 μm. Irregular deviations are visible across the entire dental arch. The highest differences are located at the distal end. A wavelike distortion of the dental arch with alternating positive and negative deviations together with a rotation of the anteriors is visible.

The visual analysis of the trueness shows a systematic deviation of the virtual 3D models to the reference model with negativ values in the anterior and molar region and positive value in the canine and premolar region (image 11 a,b). Maximum differences in the second molar area occur up to 170μm. The model is distorted along the sagittal axis on both sides (image 11a,b).

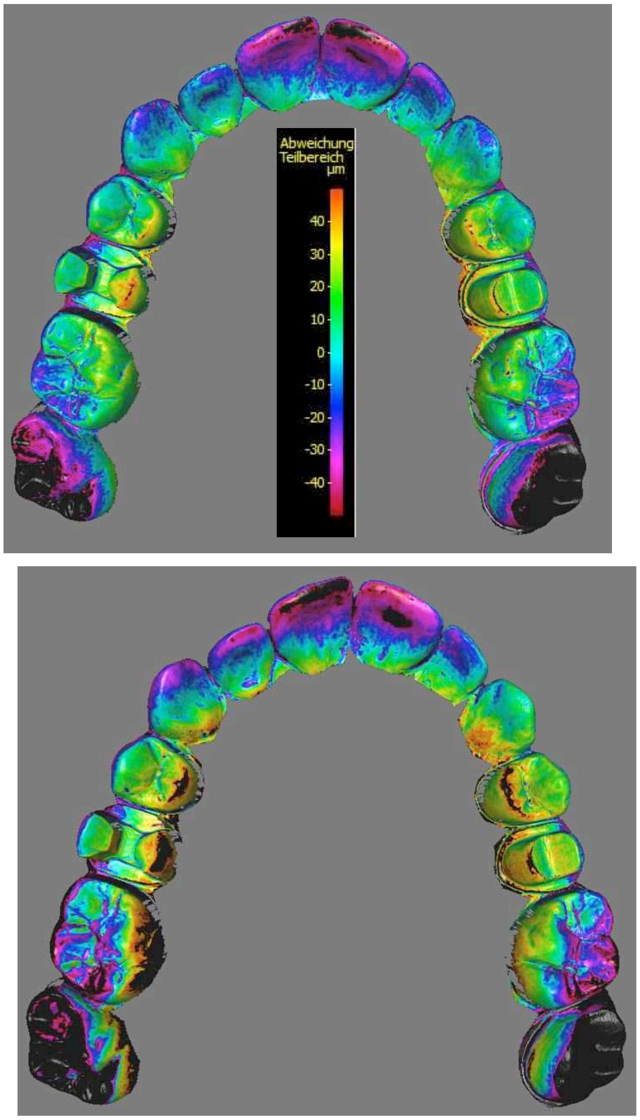


Image 11 a,b: Difference map of trueness measurement of the digital impression. Color difference map is set to -50μm to +50μm. A systematic distortion along the sagittal axis is visible. Negative deviations are located in the anterior and molar region and positive deviations in the premolar regions up to 50μm. The distal end of the dental arch differs up to 170μm

Discussion

Basis of our testing method is a scanner based on focus variation. A modulated white light is projected onto the model surface. The reflected light is measured with an objective with a low field of depth. The system is capable to measure large objects up to 10x10x10cm edge length. For small objects, different magnification lenses can be used to reduce the measure point size down to 50nm.

Evaluation of trueness and precision multiple measurements of a testing object from different directions and angulations were compared. Filter algorithms and calibration errors of the scanner will be visible by comparison of scans from different directions. However, not visible in this testing procedure is only a linear scale error in x-, y- and z- axis with the same amount. But this would be easily detectable with a length measure of a testing normal.

According to our results, trueness and precision of the new reference scanner is extremely high for scanning dental morphologies of a full arch model. For comparison, the Laserscan 3D pro, serving as reference before yielded a trueness of 10-13μm scanning a quadrant (Mehl, Gloger, Kunzelmann, & Hickel, 1997)(Mehl et al., 2009). Up to now, we are not aware of any other system, that is possible to scan sophisticated tooth surfaces with this high trueness and precision over an area up to 6cm in square. Other studies work with geometrical forms, that are verified with CMM machines. CMM`s also show high trueness and precision. But these machines are only aquiring a small amount of points from the models surface. And for a precise model with CMM, you need to know the shape of the surface before scanning (del corso 2009lit). That is ,for individual tooth surfaces, not possible. Also the tip of the tactile probe has a certain diameter. That means, little morphological structures like fissure lines and gingival margins cannot be detected with these systems. With the new reference scanner it is possible to aquire the dental surface without prior knowledge of the morphology. Some manufacturer gave their dental scanners accuracies from 10 μm to 30 μm. But these values are measured on small models or geometrical defined testing blocks with up to 10mm length (Quelle van der Zel).

In many studies, models are scanned with reference scanners, where the accuracy ofthe scanner is not described (lit). Persson et al (lit) used the same digitization device for reference and testing measurements. So the accuracy of the reference scanner is not higher than the deviations they measure. The new reference scanner delivers an accuracy that is significant ($p<0.001$) higher than the deviations from the conventional and digital impression. The comparison of only 80 percent of the scanned surface is addicted to the measurement process. Neither there is a manual filtering of outliers or data errors nor manual trimming the model to specific geometries. So we do have certain scattered surface points with errors and areas, with only little surface points. The margin of every scanned model is also slightly different. In these areas, the difference measurement is not predictable to find the correct nearest signed neighbour. Therefore a certain area, the lowest 10% and the highest 10% of the difference values is not taken for comparisons. Yet with 80 percent of the scanned surface, the difference analysis represents more model surface than a mean value with root mean square deviation that only consists of 66% of the measured differences, a value which mainly was used in other studies (Luthardt et al., 2003)(Quaas et al., 2007). Other studies use the accuracy of the final restoration for evaluation the impression technique (Syrek et al., 2010)(Del'Acqua, Arioli-Filho, Compagnoni, & Mollo Fde, 2008). This measurements are in the end again only linear distance measurements and cannot evaluate threedimensional deviations of the impression method.

With a accuracy between 3μm and 10μm, the reference scanner is significant below the deviations of conventional full arch impressions and therefore suitable for these accuracy and precision measurements. With the increasing possibilities of CAD/CAM systems, like virtual articulation, production of removable partial or complete dentures, it is very important to gain accurate data not only from the preparation, but also from the entire dental arch.

The deviation of the gypsum model from the conventional impression with a polyvinyether material show very low deviation across the entire dental arch. The higher deformations in the second molar regions may be due to the standard impression tray. Brosky et al also found impressions with larger deformations in a testing group with standard impression trays, however not located in the same area (Brosky, Major, Delong, & Hodges, 2003). In this study he measured mean deviations from 27μm to 312μm were most measurements are ranged from 27 to 83μm. This result is, however a different analysis method comparing more percent of the scanned surface was used, in good company to our results for the conventional impression trueness. The differences of this threedomensional difference analysis can`t be compared to studies with linear distance measurements with accuracies of about 10μm for conventional impression materials (Wostmann et al., 2009)(Balkenhol, Ferger, & Wostmann, 2007)(Caputi & Varvara, 2008)(Chandran et al., 2010).

The digital impressions with the CEREC Bluecam show higher deviations from the reference model resulting in a significant ($p<0.001$) lower precision and trueness compared to the conventional impression group. The pattern of deviation in the sagittal axis in one quadrant was also revealed in former studies (Mehl et al., 2009) (Luthardt, Loos, & Quaas, 2005). The deviations in the anterior region may be due to the creation of the full arch scan by combining two overlapping partial scans of both quadrants (Manufacturers recommendation, Cerec Connect Help system, Operators manual, Full Arch Impression). The registration area is the anterior region from canine to canine. In the anterior regions, with less structured tooth surface and steep inclines, more error with the optical impression can occur. It is most assumable, that the superimposition process leads to that kind of deviations. These two errors seems to be systematic and maybe reduced or passed by with further software improvement.

Balkenhol, M., Ferger, P., & Wostmann, B. (2007). Dimensional accuracy of 2-stage putty-wash impressions: influence of impression trays and viscosity *Int J Prosthodont*, *20*(6), 573-575. United States.

Beuer, F., Schweiger, J., & Edelhoff, D. (2008). Digital dentistry: an overview of recent developments for CAD/CAM generated restorations *Br Dent J*, *204*(9), 505-511. doi:10.1038/sj.bdj.2008.350

Brosky, M., Major, R., Delong, R., & Hodges, J. (2003). Evaluation of dental arch reproduction using three-dimensional optical digitization *J Prosthet Dent*, *90*(5), 434-440.

Brosky, M., Pesun, I., Lowder, P., Delong, R., & Hodges, J. (2002). Laser digitization of casts to determine the effect of tray selection and cast formation technique on accuracy *J Prosthet Dent*, *87*(2), 204-209.

Caputi, S., & Varvara, G. (2008). Dimensional accuracy of resultant casts made by a monophase, one-step and two-step, and a novel two-step putty/light-body impression technique: an in vitro study *J Prosthet Dent*, *99*(4), 274-281.

Chandran, D., Jagger, D., Jagger, R., & Barbour, M. (2010). Two- and three-dimensional accuracy of dental impression materials: effects of storage time and moisture contamination *Biomed Mater Eng*, *20*(5), 243-249. Netherlands. doi:10.3233/BME-2010-0638

Del'Acqua, M., Arioli-Filho, J., Compagnoni, M., & Mollo Fde, A. J. (2008). Accuracy of impression and pouring techniques for an implant-supported prosthesis *Int J Oral Maxillofac Implants*, *23*(2), 226-236.

Delong, R., Heinzen, M., Hodges, J., Ko, C., & Douglas, W. (2003). Accuracy of a system for creating 3D computer models of dental arches *J Dent Res*, *82*(6), 438-442.

Fasbinder, D. (2010). Digital dentistry: innovation for restorative treatment *Compend Contin Educ Dent*, *31 Spec No 4*, 2-11; quiz 12. United States.

Hoyos, A., & Soderholm, K. (2011). Influence of tray rigidity and impression technique on accuracy of polyvinyl siloxane impressions *Int J Prosthodont*, *24*(1), 49-54. United States.

Luthardt, R., Kuhmstedt, P., & Walter, M. (2003). A new method for the computer-aided evaluation of three-dimensional changes in gypsum materials *Dent Mater*, *19*(1), 19-24.

Luthardt, R., Loos, R., & Quaas, S. (2005). Accuracy of intraoral data acquisition in comparison to the conventional impression *International journal of computerized dentistry*, *8*(4), 283-294.

Luthardt, R., Sandkuhl, O., Herold, V., & Walter, M. (2001). Accuracy of mechanical digitizing with a CAD/CAM system for fixed restorations *Int J Prosthodont*, *14*(2), 146-151.

Mehl, A., Ender, A., Mörmann, W., & Attin, T. (2009). Accuracy testing of a new intraoral 3D camera *International journal of computerized dentistry*, *12*(1), 11-28.

Mehl, A., Gloger, W., Kunzelmann, K., & Hickel, R. (1997). A new optical 3-D device for the detection of wear *J Dent Res*, *76*(11), 1799-1807.

Perakis, N., Belser, U., & Magne, P. (2004). Final impressions: a review of material properties and description of a current technique *Int J Periodontics Restorative Dent*, *24*(2), 109-117.

Persson, A., ODEN, A., ANDERSSON, M., & Sandborgh-Englund, G. (2009). Digitization of simulated clinical dental impressions: virtual three-dimensional analysis of exactness *Dent Mater*, *25*(7), 929-936.

Piwowarczyk, A., Ottl, P., Buchler, A., Lauer, H., & Hoffmann, A. (2002). In vitro study on the dimensional accuracy of selected materials for monophase elastic impression making *Int J Prosthodont*, *15*(2), 168-174.

Quaas, S., Rudolph, H., & Luthardt, R. (2007). Direct mechanical data acquisition of dental impressions for the manufacturing of CAD/CAM restorations *J Dent*, *35*(12), 903-908.

Syrek, A., Reich, G., Ranftl, D., Klein, C., Cerny, B., & Brodesser, J. (2010). Clinical evaluation of all-ceramic crowns fabricated from intraoral digital impressions based on the principle of active wavefront sampling *J Dent*, *38*(7), 553-559. England. doi:10.1016/j.jdent.2010.03.015

Vlaar, S., & van der Zel, J. (2006). Accuracy of dental digitizers *Int Dent J*, *56*(5), 301-309.

Wettstein, F., Sailer, I., Roos, M., & Hammerle, C. (2008). Clinical study of the internal gaps of zirconia and metal frameworks for fixed partial dentures *Eur J Oral Sci*, *116*(3), 272-279. Denmark. doi:10.1111/j.1600-0722.2008.00527.x

Wostmann, B., Rehmann, P., & Balkenhol, M. (2009). Accuracy of impressions obtained with dual-arch trays *Int J Prosthodont*, *22*(2), 158-160.