# Evaluation of oral scanning in comparison to impression using three-dimensional registration

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## ABSTRACT

Crown and bridge restorations are one of the main treatment methods in fixed prosthodontics. The fabrication requires data on the patient's denture shape. This information is generally obtained as a hard copy from an impression mold. Alternatively, one can acquire the data electronically using oral optical three-dimensional (3D) imaging techniques, which determine the surface of the denture. The aim of the study was to quantitatively compare the accuracy of three dimensional scanning with that of conventional impressions and give a statement how far the scanner provides a clinical alternative with equal or better precision. Data from 10 teeth were acquired in the dental office with a polyether impression material and an oral scanner. Data from the impressions were digitalized by means of micro computed tomography. The data were then 3D registered to identify the potential differences between impression and optical scan. We could demonstrate that the oral scanner's data and the conventional impressions are comparable.

**Keywords:** Tooth restoration, oral scanner, registration, micro computed tomography, digital work flow, Lava™ C.O.S., displacement field

## 1. INTRODUCTION

For the fabrication of prosthodontic restorations, a three-dimensional (3D) model of the damaged denture is necessary. Elastomeric impression materials are largely used to record the morphology of hard and soft dental tissues during dental treatment or to record the relationship between teeth and the surrounding tissue. The clinical success of fixed prosthodontic procedures is dependent upon the dimensional accuracy of tooth impression procedures, from which models for tooth restoration are derived. For example, the presence of gaps between restoration and tooth can lead to infection due to bacterial infiltration and ultimately to the failure of the restoration. A variety of studies exists that examines various all-ceramic crown systems with a wide range of marginal openings from 0 to 313 $\mu$m and a reported mean marginal opening of 155 $\mu$m [1, 2]. A marginal gap ranging from 25 to 40 $\mu$m for cemented restorations has been suggested as a clinical goal [3]. McLean and Fraunhofer examined more than 1000 crowns over a 5-year period and concluded that a marginal opening of 120 $\mu$m was clinically acceptable [4].

A variety of factors that influence the precision of dental casts have been identified, including correct manipulation of impression materials [5–8]. The advance in materials and development of techniques has been essential to improve the accuracy of impressions. Of the several impression protocols suggested, the double-mix techniques, in which two materials of different viscosity are used together, were preferred especially when polyether and vinyl polysiloxane materials were adopted. A single-step technique, in which both materials polymerize simultaneously, reduces chair-side time and saves impression material [9–11]. The use of a custom tray may have a significant effect as well, and offers an advantage by providing a uniform thickness of impression material to improve the accuracy of the working cast [8]. The main objective in stock tray construction is to provide a rigid tray, which provides retention for the impression material [12].

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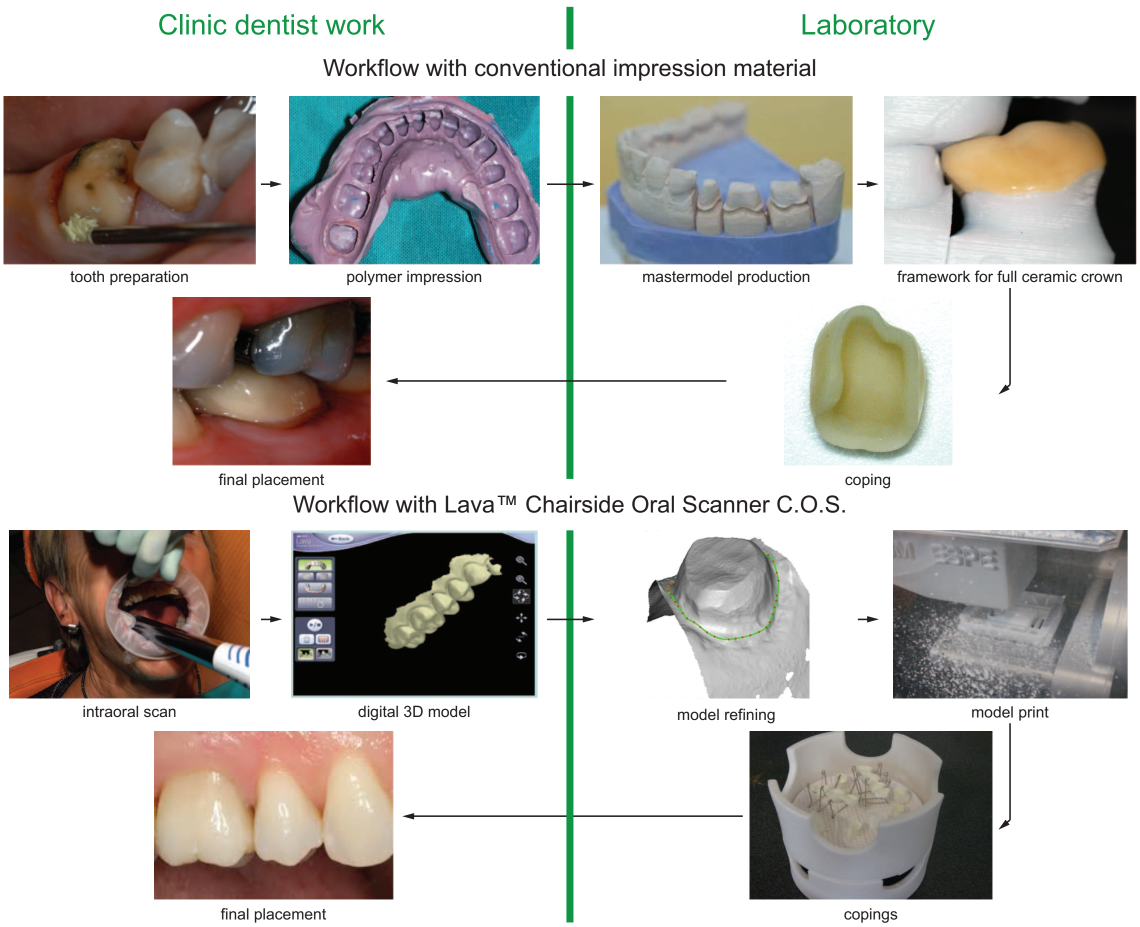


Figure 1. Schematic representation of the work flow of tooth fixed prosthodontic restorations. On the top half, the standard procedure is shown: After the tooth preparation and the exsiccation, the dentist makes an impression with a conventional impression material with an individualized tray. The impression and the bite registration are transmitted to the laboratory, where a cast is produced, on which the restoration is modeled. Finally, the veneered restoration is returned to the office for implantation. On the bottom half, the procedure with CAD/CAM technology is shown: The intra-oral scan is transmitted after having been acquired and a digital model of the dentition is generated. The data are sent to the scanner manufacturer, where they are processed for restoration/model is milled. The restoration is then sent to the technician for veneering before implantation.

We are currently in an era of high performance materials such as highly sintered glass or alumina- and zirconia-based ceramics. Also, fabrication combined with a computer-assisted fabrication system and networks are becoming increasingly available [13]. In addition to the conventional methods of fixed prosthodontic manufacture by dental technicians (sintering, casting, pressing) there is the possibility of grinding restorations out of a preformed block, either by means of Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) or by using a copy milling unit, the so-called *subtractive methods*. In this context differentiation is between analogue and digital systems. Analogue systems (copying methods) are further separated into copy grinding and copy milling. Analogue copying methods include two fundamental steps, beginning with the fabrication of the so-called pro-inlay, which will be scanned and copied in a second step. Digital systems, which may be used directly or indirectly, always distinguish between three steps: three-dimensional surface scanning, CAD-modeling of the restoration and fabrication of the restoration [14]. Figure 1 qualitatively illustrates the analogies and differences between conventional casting and the CAD/CAM technology.

The accuracy of CAD/CAM-based systems is less well known compared to dental casts, which are still the gold standard. Only few long-term studies investigating CAD/CAM restorations exist [14]. The inevitable covering with powder can cause errors of about 20 to 40 $\mu$m with direct methods, although improvements have been made. It was shown that a fitting accuracy of 90 $\mu$m is achievable with the use of powder, and of about 63 $\mu$m with the use of a water soluble color [15]. Vögtlin *et al.* have shown *in vitro* that the oral scanners achieve a precision of 190 $\mu$m in the mean local displacements [16], indicating the high similarity of CAD/CAM data and casts, where mean pixel displacements of 120 $\mu$m were reported. However, scanner-based methods are still less precise and the reconstructions are limited to very few teeth [16].

Micro computed tomography ($\mu$CT) offers the possibility to three-dimensionally image dental casts. To quantitatively compare the recently available optical 3D scanning approach with the established impressions under clinical conditions, ten casts acquired in the dental office were scanned with a Skyscan 1174$^{TM}$(Skyscan, Kontich, Belgium) and compared with the corresponding CAD/CAM data, acquired with the oral scanner C.O.S. (3M ESPE AG, Rüschlikon, Switzerland), by means of volumetric data registration. Thus, the 3D datasets can be directly compared by means of scalar parameters including mean and maximum displacements and scaling factors [3, 4, 8, 12, 17–19]. The aim of the present study is to quantitatively compare the achievable precision of oral scanners with the conventional approach using impressions under clinical conditions.

# 2. MATERIALS AND METHODS

## 2.1 Clinical dental impressions

A retraction thread was placed around the entire sulcus of the prepared tooth and then a thicker thread was placed on top of this. This keeps the area dry where the impression is being taken. Before the impression is taken, any residue of the retraction thread is removed by rinsing and drying. Simultaneously the two component impression material is mixed in the Pentamix (3M ESPE, Neuss, Germany). The paste is filled in the tray (Simul Tray®, Gnathojust Quadrant orange, swissdental, Switzerland). The tray is positioned immediately in the mouth. The residence time in the mouth must always be 3 minutes, regardless of the previously needed processing time. Only when using a sufficient pressure obtained by clenching the teeth, the flowable silicone paste can penetrate into the narrowest margins also from the opposing jaw. When the setting time has elapsed, the impression is removed from the mouth. Specimens were given a four digit number corresponding to the patient and a two digit number identifying the tooth according to the FDI World Dental Federation notation.

## 2.2 Optical data acquisition

After crown preparations, soft-tissue retraction was performed and the tooth surfaces were cleaned and dried. The teeth and soft tissues were isolated and lightly sprayed with a titanium-dioxide powder to create a surface with reasonable reflectance. The powder supports the recording of the 3D models providing increased contrast and thus allows for increased scanning speeds. The Lava C.O.S. intra-oral camera automatically begins the data acquisition when it is suitably positioned, i.e. within the focal range between 5 to 15 mm from the teeth and soft tissue. Scanned areas with sufficient data density appear white on the monitor while areas with partial data appear in pink. Any areas remaining black within the desired scan field have an insufficient data density. This allows for real-time management of the scanning process and the volume model [20]. After the prepared teeth have been recorded, further teeth in the quadrant or arch might be scanned to complete the desired model. The touch-screen monitor allows the digital model to be rotated, magnified, and evaluated through 3D stereographic review to assess accurate recording of the dentition [21]. Two separate scans are recorded for the preparation and the opposing jaw. The data file is electronically transmitted to 3M ESPE for the fabrication of the working models.

## 2.3 Synchrotron radiation-based micro computed tomography

The SR$\mu$CT measurement was performed at the beamline W2 at HASYLAB (DESY, Hamburg, Germany) operated by the Helmholtz Zentrum Geesthacht [22]. To image the whole specimen, 9 scans at different height levels were measured. Each scan of 1441 projections over 360° was acquired with an asymmetric rotation axis [23] to obtain a better spatial resolution. The photon energy was set to 20 keV and the effective image pixel size to 4.75 $\mu$m. The spatial resolution of the projections, amounting to 6.2 $\mu$m, and was determined by the 10% value of the modulation transfer function (MTF) of a highly X-ray absorbing edge [24]. Prior to reconstruction, the data was binned by a factor of two to reduce noise and data size [25].

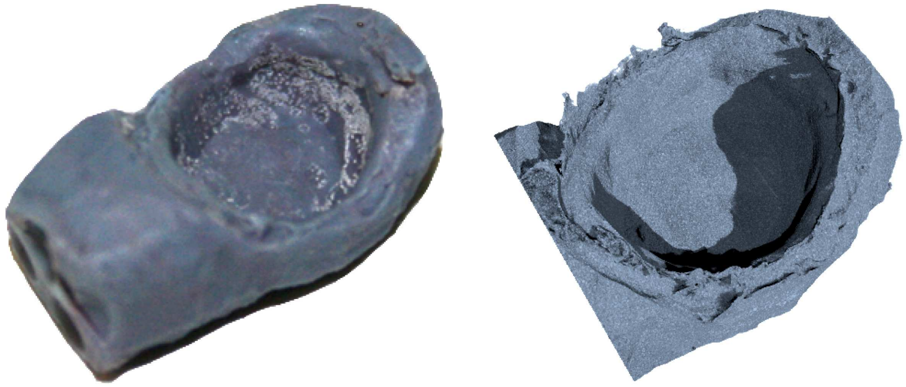

Figure 2. A photograph of an impression (left) and the three-dimensional rendering of the corresponding SR$\mu$CT dataset in false colors.

### 2.4 Microcomputed tomography using a laboratory source

Tomographic data acquisition was performed with a Skyscan 1174$^{TM}$(Skyscan, Kontich, Belgium) at an acceleration voltage of 50 kVp and beam current of 800 $\mu$A. The pixel sizes ranged from 20 to 29 $\mu$m, depending on specimen size. A 0.5 mm-thin Al filter was placed between source and specimen used to increase the mean X-ray energy and reduce beam-hardening artifacts. 1201 projections of 1024 $\times$ 1024 pixels were acquired for each scan with 3 s exposure time per projection, resulting in an approximate scan time of 1 h. The data were reconstructed with the software NRecon (Skyscan, Kontich, Belgium), based on a modified Feldkamp algorithm. The software included corrections for beam hardening and ring artifacts.

Before data acquisition, any material which could be removed without any effect on the outcome was cut from the impressions. Holes in the polymer, which occurred where upper and lower teeth meet, were filled with the same polyether paste as the impression.

### 2.5 Data registration

The computer aided design (CAD) data of the optical scans was converted to voxel data with a voxel length equal to that of the corresponding tomographic datasets with a Matlab® script (MATLAB 2010b, The MathWorks, Natick, USA). For easier handling, the individual teeth were cut from the whole datasets with the software MeVisLab 2.3 (MeVis Medical Solutions AG and Fraunhofer MEVIS, Germany). Both optical and tomographic data were binarized, with material corresponding to unity and surrounding air to zero. The datasets were manually pre-registered using an IDL (IDL 6.8, Exelis, Boulder, USA) routine and a common volume was extracted for each specimen. The pre-registration was performed with nine degrees of freedom, namely three translational, three rotational and three scaling factors [26]. Subsequently, the pre-registered data were affinely and non-rigidly registered using a hierarchical image sub-division (hereafter termed non-rigid) algorithm [27]. The affine registration yields nine parameters, analogously to the pre-registration [28].

In addition, non-rigid registration was used to determine local differences between optical scanner data and dental casts. Since the voxel data were binarized, only the voxels belonging to the surface of the objects contain meaningful information concerning object similarity.

## 3. RESULTS

### 3.1 $\mu$CT scan precision

Figure 2 shows, on the left, a photographic image of the specimen, and on the right, a 3D rendering of the SR$\mu$CT scan in comparable colors. These data demonstrate the high spatial resolution of the 3D SR$\mu$CT data. The SR$\mu$CT and $\mu$CT data of specimen p2917 t16 were affinely registered to determine the pixel size precision of the Skyscan$^{TM}$ scanner. The voxel length of the Skyscan data resulted to be 95.8% of that of the SR$\mu$CT data. This value was used to correct the pixel size of all acquired Skyscan datasets.

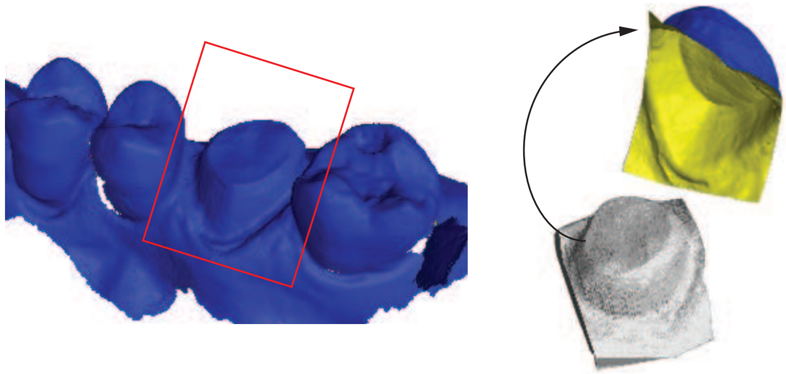

Figure 3. The individual teeth are cut from the optical scan data. The surfaces are converted to point clouds and subsequently filled with voxels.

### 3.2 CAD/CAM vs. $\mu$CT

The individual teeth were extracted from the optical scan (cp. Figure 3). The surfaces are converted to point clouds and subsequently filled with voxels representing material. The combination of manual pre-registration and affine registration of the CAD/CAM data with the $\mu$CT scans yields the global size difference between the datasets as scaling factors in the three orthogonal directions mesial-distal (MD, along the denture), buccal-intraoral (BI, in the direction from the tongue to the cheek), and occlusal-cervical (OC, from the root of the tooth to the crown). Table 1 lists these scalings, corrected with the factor from section 3.1, as well as the total volumetric difference. The values range from 95% to 105% indicating reasonable agreement between CAD/CAM and $\mu$CT data. The highest discrepancy of 98.8% $\pm$ 1.6% is found in occlusal-cervical direction. It has to be noted that in this direction only the occlusal surface of the tooth is available, while no structure belonging to the tooth root is available for registration. Therefore, a higher imprecision was expected. Nonetheless, reasonable agreement between the sizes of CAD/CAM and $\mu$CT was found. Figure 4 illustrates the procedure. The improvement of dataset similarity can be seen.

Table 1. Scaling factors after affine registration. Directions are: buccal-intraoral - BI, mesial-distal - MD, occlusal-cervical - OC. Errors correspond to the standard deviation.

| **specimen** | **Scaling in BI** [%] | **Scaling in MD** [%] | **Scaling in OC** [%] | **Total vol. scaling** [%] |
|---|---|---|---|---|
| **p0856 t14** | 101.3 | 101.0 | 97.5 | 99.8 |
| **p0856 t15** | 103.4 | 98.1 | 99.1 | 100.5 |
| **p0856 t16** | 96.8 | 98.5 | 99.8 | 95.1 |
| **p2917 t16** | 97.2 | 98.1 | 98.2 | 93.6 |
| **p3437 t27** | 98.2 | 99.3 | 103.7 | 98.5 |
| **p3543 t16** | 99.7 | 101.1 | 100.6 | 101.4 |
| **p4485 t23** | 102.6 | 101.1 | 100.1 | 103.8 |
| **p4485 t24** | 99.9 | 98.4 | 98.7 | 96.9 |
| **p4485 t25** | 96.6 | 95.7 | 93.7 | 86.6 |
| **p4943 t44** | 104.7 | 99.2 | 101.3 | 105.2 |
| **mean** | 100.2 $\pm$ 2.9 | 99.2 $\pm$ 2.2 | 98.8 $\pm$ 1.6 | |

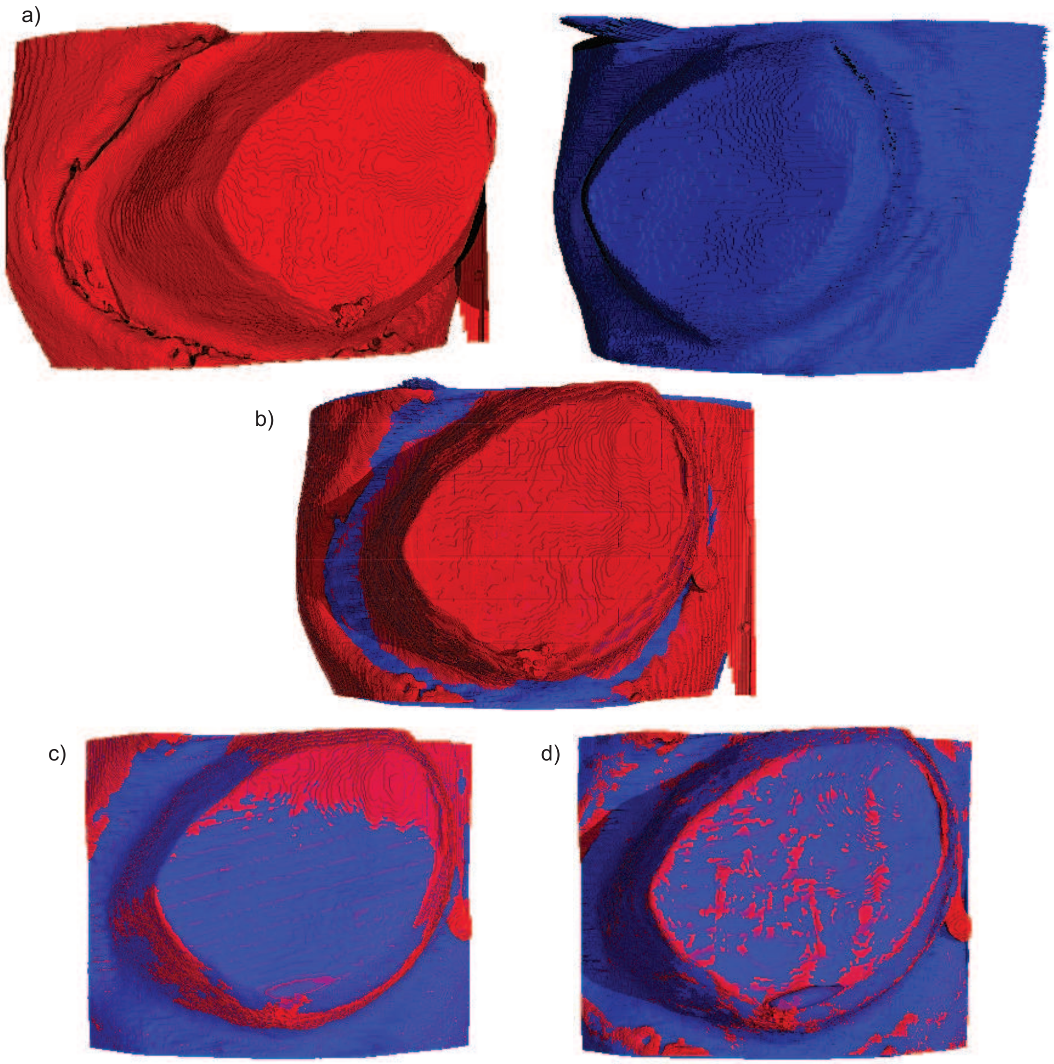


Figure 4. Illustration of the subsequent steps of dataset registration. First, the Skyscan (red) and optical scanner (blue) data are manually registered (b), then an affine registration, comprising three translational, three rotational and three scaling parameters is performed (c). Finally, the optical scanner dataset is locally deformed to match the tomographic reference (d).

For a perfect fit of a ceramic restoration, the surface shape is ultimately relevant. Therefore, even if the overall size of the prepared tooth is adequately reproduced, local deformations might reduce the quality of the restoration. To access the local differences, non-rigid registration was performed which yields the pixel displacements. Table 2 lists mean and maximal deviations of the pixels on the surface of the CAD/CAM datasets, as well as a clinical evaluation given by a clinical expert during restoration placement. The mean displacements lie between 90 and 220 $\mu$m, while the maximal found discrepancy amounts to over 600 $\mu$m. The clinical ratings are given as follows: 1 - perfect fit, no additional chairside processing necessary, 2 - reasonable fit, only marginal post-processing required, 3- moderate post-processing required, 4 - substantial post-processing required. Generally, reasonable agreement between clinical rating and mean pixel displacement was found. A rating of 2 was assigned to specimens presenting mean displacements below approximately 150 $\mu$m. Overall, mean pixel displacements of up to 150 $\mu$m are tolerable without excessive additional effort for the clinician.

Figure 5 illustrates the local displacements of the surface pixels based on two examples. Specimen p3543 t16, on the left, exhibits pixel displacements usually below 150 $\mu$m. In specimen p2917 t16, on the right, a region

Table 2. Mean and maximal displacements of points on the surface of the specimens. Errors are given as standard deviation. The clinical rating was given by an expert clinician during restoration placement.

| Specimen | Mean [$\mu$m] | Maximal [$\mu$m] | Clinical rating |
|---|---|---|---|
| **p0856 t14** | $88 \pm 44$ | 213 | 2 |
| **p0856 t15** | $114 \pm 50$ | 269 | 2 |
| **p0856 t16** | $161 \pm 84$ | 471 | 2 |
| **p2917 t16** | $216 \pm 118$ | 655 | 4 |
| **p3437 t27** | $101 \pm 34$ | 290 | 2 |
| **p3543 t16** | $75 \pm 47$ | 370 | 2 |
| **p4485 t23** | $141 \pm 67$ | 419 | 3 |
| **p4485 t24** | $77 \pm 35$ | 217 | 3 |
| **p4485 t25** | $204 \pm 57$ | 377 | 3 |
| **p4943 t44** | $158 \pm 41$ | 268 | 3 |

showing high deformation can be seen in red. Here we can see a maximum deviation of 655 $\mu$m. Reduced precision of the tooth surface acquisition could be caused by poor accessibility of the oral cavity by the camera due to individual anatomic conditions such as a small mouth opening, high palate or a large tongue, so that the merging of the video sequences was imprecise. Alternative error sources arise from insufficient powdering of the deeper structures, resulting in high light reflection. Highest displacements were found to lie in BI direction, except for specimen p4485 t24, where they were located in the occlusal region, which means that the functional occlusion has to be adjusted by grinding for specimen p4485 t25 where they were in the BI direction in the distal areas, and p4943 t44, where displacements were rather homogeneously distributed over the specimen. Interestingly, these are also the specimens where the clinical rating does not correlate well with the mean displacements obtained from data registration.

## 4. DISCUSSION

The optical scan provides information comparable to the conventional impression (cp. Table 2). In the areas of undercuts small differences seem to exist between the two techniques. The application of CAD/CAM technology in dentistry provides an innovative dental service. Considering the total work flow, from impression to cast fabrication to finishing the crown, the conventional laboratory technology and dental technician skills remain important. Therefore, we must combine scanning technology and conventional technology to meet patient demand. For the production of a fixed prosthetic restoration multiple steps are required, so the clinical evaluation can not be attributed only to the molding step.

The scanning technologies provide several benefits for the patient including enhanced intrinsic factors in relation to the material properties like no smell, no unpleasant taste, and thus no gag reflex and the ability to make the scanning within minutes [5]. Therefore, this technology will gradually replace the conventional material-based impression. Further investigations will, however, be needed to validate the precision of the scanning similar to the work of Vögtlin *et al.* [16] who performed a thorough *in vitro* investigation. This study demonstrated that the scanning is still restricted to a limited number of teeth and cannot yet applied to the entire jaw. We therefore recommend scanning of individual teeth. From an engineering point of view the 3D registration of surface data from scanning and volumetric data from $\mu$CT of impressions is demanding. Much effort had to be invested to reach the goal. Manual pre-registration is a vital step. The correlation of the obtained quantities with the clinical experience will be the topic of a forthcoming publication. Although SR$\mu$CT generally yields higher spatial and density resolutions compared to tube-based $\mu$CT, the $\mu$CT data of a relatively simple system yielded values with sufficient precision, as found in previous studies [29–32].

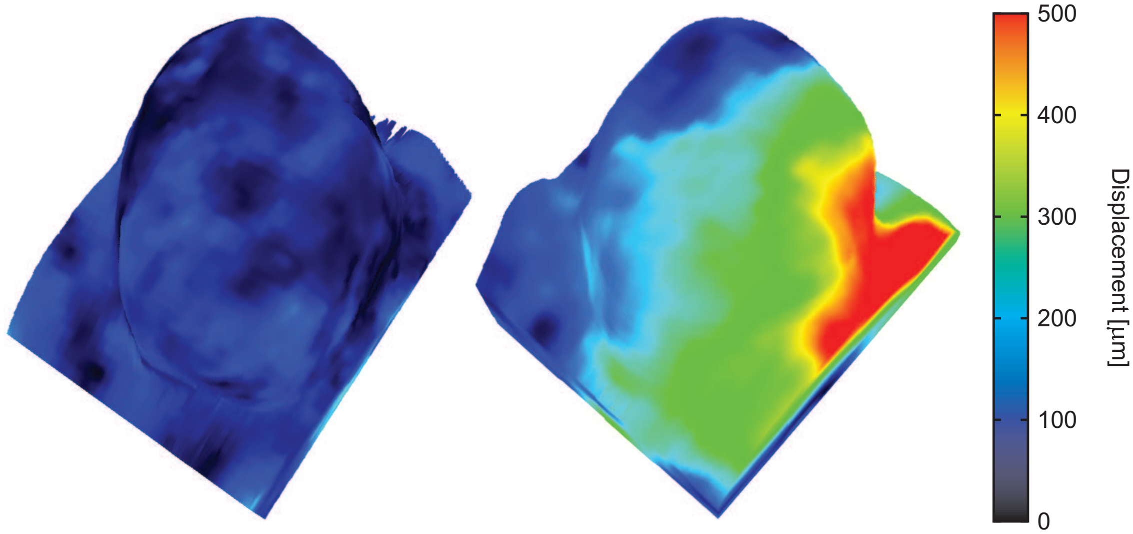


Figure 5. Pixel displacement of the optical scanner data after registration with $\mu$CT data. On the left, specimen p3543 t16 is shown. Overall pixel displacements usually below 150 $\mu$m indicate high similarity between the datasets. On the right, specimen p2917 t16 is shown. As also apparent from Table 2 that a higher degree of mismatch is visible in the mesial-distal direction, with its maximum on the distal side.

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## REFERENCES

[1] Adair, P. J. and Grossman, D. G., "The castable ceramic crown," *Int. J. Periodontics Restorative Dent.* **4**, 32–46 (1984).

[2] Pera, P., Gilodi, S., Bassi, F., and Carossa, S., "In vitro marginal adaptation of alumina porcelain ceramic crowns," *J. Prosthet. Dent.* **72**, 585–590 (1994).

[3] [*Guide to Dental Materials and Devices*], ch. ANSI/ADA Specification No. 8 for zinc phosphate cement, 87–88, American Dental Association (1970).

[4] Kelly, J. R., Nishimura, I., and Campbell, S. D., "Ceramics in dentistry: Historical roots and current perspectives," *J. Prosthet. Dent.* **75**, 18–32 (1996).

[5] Hamalian, T. A., Nasr, E., and Chidiac, J. J., "Impression materials in fixed prosthodontics: Influence of choice on clinical procedure," *J. Prosthodont.* **20**, 153–160 (2011).

[6] Franco, E. B., da Cunha, L. F., Herrera, F. S., and Benetti, A. R., "Accuracy of single step versus 2-step double mix impression technique," *ISRN Dent.* **2011**, 341546 (2011).

[7] Thongthammachat, S., Moore, B. K., Barco, 2nd, M., Hovijitra, S., Brown, D. T., and Andres, C. J., "Dimensional accuracy of dental casts: Influence of tray material, impression material, and time," *J. Prosthodont.* **11**, 98–108 (2002).

[8] Cunningham, D., [*A study of the comparative accuracy of elastic impression materials utilizing partial denture impression*], Indiana University School of Dentistry (1961).

[9] Craig, R. G., "Evaluation of an automatic system for an addition silicone impression material," *J. Am. Dent. Assoc.* **110**, 213–215 (1985).

[10] Johnson, G. H. and Craig, R. G., "Accuracy of addition silicones as a function of technique," *J. Prosthet. Dent.* **55**, 197–203 (1986).

[11] Caputi, S. and Varvara, G., "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**, 274–281 (2008).

[12] Millenstein, P., Maya, A., and Sequra, C., "Determining the accuracy of stock and custom tray impression/casts," *J. Oral Rehabil.* **25**, 645–648 (1998).

[13] Miyazaki, T. and Hotta, Y., "CAD/CAM systems available for the fabrication of crown and bridge restorations," *Aust. Dent. J.* **56 Suppl 1**, 97–106 (2001).

[14] Hickel, R., Dasch, W., Mehl, A., and Kremers, L., "CAD/CAM–fillings of the future?," *Int. Dent. J.* **47**, 247–258 (1997).

[15] Hembree, Jr., J. H., "Comparison of fit of CAD/CAM restorations using a direct and an indirect technique," *Miss. Dent. Assoc. J.* **53**, 23–24 (1997).

[16] Vögtlin, C., Schulz, G., Jäger, K., Liebreich, T., Weikert, S., and Müller, B., "Comparison of denture models by means of micro computed tomography," *Proc. SPIE* **8506** (2012).

[17] Johnson, G. H. and Craig, R. G., "Accuracy of four types of rubber impression materials compared with time of pour and a repeat pour of models," *J. Prosthet. Dent.* **53**, 484–490 (1985).

[18] Bomberg, T. J., Hatch, R. H., and Hoffman, Jr., W., "Impression material thickness in stock and custom-trays," *J. Prosthet. Dent.* **54**, 170–172 (1985).

[19] Rueda, L. J., Sy-Munoz, J. T., Naylor, W. P., Goodacre, C. J., and Swartz, M. L., "The effect of using custom or stock trays on the accuracy of gypsum casts," *Int. J. Prosthodont.* **9**, 367–373 (1996).

[20] Schoenbaum, T., "Decoding CAD/CAM and digital impression units," *Dent. Today* **29**, 140–145 (2010).

[21] McMaster, D., Cohen, B., and Spitz, S., "Digital workflow," *Dent. Econ.* **8**, 30–36 (2008).

[22] Beckmann, F., Herzen, J., Haibel, A., Müller, B., and Schreyer, A., "High density resolution in synchrotron-radiation-based attenuation-contrast microtomography," *Proc. SPIE* **7078**, 70781D (2008).

[23] Müller, B., Bernhardt, R., Weitkamp, T., Beckmann, F., Bräuer, R., Schurigt, U., Schrott-Fischer, A., Glueckert, R., Ney, M., Beleites, T., Jolly, C., and Scharnweber, D., "Morphology of bony tissues and implants uncovered by high-resolution tomographic imaging," *Int. J. Mater. Res.* **98**, 613–621 (2007).

[24] Müller, B., Thurner, P., Beckmann, F., Weitkamp, T., Rau, C., Bernhardt, R., Karamuk, E., Eckert, L., Buchloh, S., Wintermantel, E., Scharnweber, D., and Worch, H., "Three-dimensional evaluation of biocompatible materials by microtomography using synchrotron radiation," *Proc. SPIE* **4503**, 178–188 (2002).

[25] Thurner, P., Beckmann, F., and Müller, B., "An optimization procedure for spatial and density resolution in hard X-ray micro-computed tomography," *Nucl. Instrum. Meth. B* **225**, 559–603 (2004).

[26] Luckow, M., Deyhle, H., Beckmann, F., Dagassan-Berndt, D., and Müller, B., "Tilting the jaw to improve the image quality or to reduce the dose in cone-beam computed tomography," *Eur. J. Radiol.* **80**, e389–e393 (2011).

[27] Andronache, A., von Siebenthal, M., Székely, G., and Cattin, P., "Non-rigid registration of multimodal images using both mutual information and cross-correlation," *Med. Image Anal.* **12**, 3–15 (2008).

[28] Müller, B., Deyhle, H., Lang, S., Schulz, G., Bormann, T., Fierz, F., and Hieber, S., "Three-dimensional registration of tomography data for quantification in biomaterials science," *Int. J. Mater. Res.* **103**, 242–249 (2011).

[29] Gugger, J., Krastl, G., Huser, M., Deyhle, H., and Müller, B., "The morphology of amputated human teeth and its relation to mechanical properties after restoration treatment," *Proc. SPIE* **7804**, 78041H (2010).

[30] Krastl, G., Gugger, J., Deyhle, H., Zitzmann, N. U., Weiger, R., and Müller, B., "Impact of adhesive surface and volume of luting resin on fracture resistance of root-canal treated teeth," *Int. Endod. J.* **44**, 432–439 (2011).

[31] Deyhle, H., Schmidli, F., Krastl, G., and Müller, B., "Evaluating tooth restorations: Micro computed tomography in practical training for students in dentistry," *Proc. SPIE* **7804**, 780417 (2010).

[32] Drews, S., Beckmann, F., Herzen, J., Brunke, O., Salmon, P., Friess, S., Laib, A., Koller, B., Hemberger, T., Müller-Gerbl, M., and Müller, B., "Comparative micro computed tomography study of a vertebral body," *Proc. SPIE* **7078**, 70780C (2008).