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ORIGINAL ARTICLE

Accuracy of digital models obtained by direct and indirect data capturing

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Abstract
Objectives With direct and indirect digitalisation, two access points to CAD/CAM-generated restorations are available. The aim of this study was to compare the accuracy of the single steps of both approaches by comparing construction datasets using a new methodology.
Material and method Twelve test datasets were generated in vitro (1) with the Lava Chairside Oral Scanner (COS) (2) by digitizing polyether impressions (IMP) and (3) by scanning the referring gypsum cast by the Lava Scan ST laboratory scanner (ST) at a time. Using an inspection software, these datasets were superimposed by a best fit algorithm with the reference dataset (REF), gained from industrial computed tomography, and divergences were analysed.
Results On the basis of average positive and negative deviations between test- and REF datasets, it could be shown that direct digitalisation accomplished the most accurate results (COS, 17 μm/−13 μm; SD±19 μm), followed by digitized polyether impression (IMP, 23 μm/−22 μm; SD± 31 μm) and indirect digitalisation (ST, 36 μm/−35 μm; SD± 52 μm). The mean absolute values of Euclidean distances showed the least values for COS (15 μm; SD±6 μm), followed by IMP (23 μm; SD±9 μm) and ST (36 μm; SD± 7 μm). The mean negative and mean absolute values of all groups were significantly different. Comparing the mean positive values of the groups, IMP and COS (p=0.082) showed no significant difference, whereas ST and COS, and ST and IMP exhibited statistically significant differences.
Conclusions Within the limitations of this in vitro study, the direct digitalisation with Lava C.O.S. showed statistically significantly higher accuracy compared to the conventional procedure of impression taking and indirect digitalisation.
Clinical relevance Within the limitations of this study, the method of direct digitalisation seems to have the potential to improve the accuracy of impressions for four-unit FDPs.

Keywords Intraoral scanner · Accuracy · Indirect data capturing · Direct data capturing · Matching · STL

Introduction

The application of computer-aided design/computer-aided manufacturing (CAD/CAM) restorations provides innovative, state-of-the-art dental service, and its application has increased significantly in the last years [1]. Generally, with indirect and direct digitalisation, two access points to the digital workflow and to digital generated dental restorations are available at the present stage [2].

Laboratory digitizing starts with a conventional impression that is poured, and the resulting model is digitized, by using one of several optical or mechanical systems [3]. As well, some systems offer the possibility to scan the impression directly without cast fabrication [4]. However, in either instance, the initial step of the highly precise digital workflow is an analogue impression. Conventional high precision impression materials, like hydrocolloid, polyether, polyvinyl or polysulfide in combination with stone casts, offer a well-known procedure to transfer the clinical situation into the laboratory [5–8]. However, some drawbacks are related to the sensitive

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process steps of this technique. In this context, the potential distortion of the impression due to limited suitability for storage, deficient dimensional stability, disinfection in antiseptic solution, partial or extensive separation of the impression material from the tray, transport into the dental laboratory at different climatic conditions and the overall long process chain has to be mentioned [9]. Additionally, the choice of the impression technique seems to influence the accuracy of dental impressions, hence the fitting of the resulting restorations [10]. Besides, discomfort for the patient like sweating, gagging, pain and partially inconvenient taste is a known issue associated with conventional impression taking. In several situations, this instability and discomfort factor might be avoided by direct data capturing, which represents a logical direct access to dental CAD/CAM. With this technique, the intraoral surfaces are captured directly in the patient' s mouth using optical technologies.

Recently, a number of intraoral scanning systems are under development or were already introduced to the dental market in Western Europe and the USA. Currently, in Germany, the systems iTero (Cadent, Inc.; Carlstadt, NJ, US), CEREC AC with Bluecam (Sirona Dental Systems; Bensheim, Germany) and the Lava C.O.S. (3M ESPE, Seefeld, Germany) are available. For certain applications, these devices offer the possibility to replace the conventional technique of impression taking.

For clinical application one central question arises. How accurate are digital impression methods compared to the conventional procedure of impression taking, cast fabrication and indirect digitalisation in the dental laboratory?

Generally, there are two possibilities to analyse the precision of these two workflows. The first one is to compare the fit of the respective restorations, and consequently the whole manufacturing process. The other way would be to compare the resulting surface tessellation language (STL) datasets, which function as basis for CAD construction, from both workflow alternatives, with a highly accurate reference dataset.

The three-dimensional discrepancies between two surface datasets can be analysed by superimposition using appropriate inspection software. Mostly, these software programs use best fit algorithms for the alignment and subsequently comparison of 3D datasets. To describe the accuracy of digital three-dimensional models, the parameters of "trueness" and "precision" are applied [11]. Referred to ISO Norm 5725–1 standard "trueness" refers to the closeness of agreement between the arithmetic mean of a large number of test results and the true or accepted reference value. The term "precision" refers to the closeness of agreement between test results, and is normally expressed in terms of standard deviations.

To receive a reference value, in this case a highly accurate 3D dataset of the reference model, several approaches, applying coordinate measuring machine (CMM), computed tomography (CT) and an optical technology based on focus variation, were described [4, 12, 13]. In the present study, the titanium reference model was measured and digitized by industrial computed tomography to obtain a highly accurate reference dataset.

The aim of this in vitro study was to compare the accuracy of three-dimensional datasets acquired from digital impression with the well-established method of conventional impressions, gypsum casts and indirect data capturing. Direct data acquisition was conducted by the Lava Chairside Oral Scanner C.O.S. (3M ESPE, Seefeld, Germany), whereas indirect data capturing was carried out with the Lava Scan ST (3M ESPE, Seefeld, Germany) laboratory scanner. The working hypothesis is that different ways of digitizing lead to different data for CAD/CAM fabrication.

Material and methods

Reference model and reference dataset

A CAD/CAM-fabricated titanium model representing a premolar and molar with a chamfer preparation for a four-unit fixed dental prostheses was used as reference model. To receive the surface reference dataset, the model was digitized by an industrial CT system (Perkin Elmer PE XRD 1620; Feinfocus FXE 225.99 at EZRT, Fürth, Germany). Industrial computed tomography uses calibrated reference objects (e.g. ball bars) to calibrate scanned volume datasets. The accuracy of the used CT system was estimated by a calibration scan of a ball bar model, and comparison with data from a standardized CMM showed a difference of the diameters of 0.003 mm. However, the size of the isotropic voxels in each measurement can be entered accurately. The voxel size after correction was 16.03 μm, which means that the accuracy of the surface measurement can be estimated about 5 μm over the entire model. To receive a surface model from the volume data, data were post-processed using a special software developed by the Fraunhofer Institute (Fürth) as commercially available products are not able to handle such an enormous amount of data. To generate a STL surface, the position of the corner points of the triangles was determined using the marching cubes method. Irrelevant surface areas and manifolds were deleted using Geomagic Qualify 10.0 (Geomagic; Morrisville, NC, USA). The resulting STL dataset was exported and defined as the reference value (REF) for this study.

Direct data capturing (Lava C.O.S.)

A stochastic pattern as a prerequisite for accurate scanning with Lava C.O.S. was generated on the model by lightly powdering with Lava Scanpowder (3M ESPE, Seefeld, Germany). The powder layer was removed by steam and renewed before each scan. Scans (n=12) were performed, and the corresponding STL datasets (COS 1–12) were exported.

Impression—gypsum cast—indirect data capturing (Lava Scan ST)

Twelve conventional monophase impressions with a polyether material (Impregum Penta; 3M ESPE) were taken in line with the manufacturer' s recommendations using light-cured custom-made trays (Palatray XL, Heraeus Kulzer; Hanau, Germany) to ensure optimal material thickness. The impressions were disinfected for 10 min (Impresept; 3M ESPE) according to clinical procedures. Twelve hours after impression taking, all trays were digitized by industrial computed tomography according to the reference model, and STL data were exported (IMP 1–12). Twenty-four hours after removal, the impressions were poured with a scannable type IV gypsum (Octa-Scan; Heraeus Kulzer), and master casts were manufactured. The indirect data capturing with the laboratory scanner Lava Scan ST was carried out at the earliest 48 h after casting, and STL data were exported (ST 1–12). Figure 1 surveys the study procedure.

Alignment of datasets

All STL datasets (REF, COS 1–12, IMP 1–12 and ST 1–12) were imported into the inspection software Qualify 12.0. To ensure a precise superimposition, the datasets were reduced to the field of interest. Therefore, all artefacts and not relevant areas below the preparation line were eliminated. Each of the 12 test datasets from COS, IMP and ST was aligned with the REF dataset by a best fit algorithm.

Analysis of 3D divergences

The software (Qualify 12.0) calculated the divergences in x-, y- and z-axis between each test and REF dataset. As well, it gave the Euclidean distances for each single measurement point, which can take positive or negative values in relation to the REF dataset, and which were used for data analysis. Divergences between a test and the reference dataset were given as mean positive and negative deviations and standard deviation (SD), respectively. Furthermore, for each alignment, the mean of absolute values of the Euclidean distances and its SD was arisen. For all 12 datasets from a single group (COS, IMP and ST), mean values and SD were calculated to compare the workflows to each other. The three-dimensional differences were calculated and displayed colour-coded by the software (Figs. 2, 3 and 4). For further evaluations and statistical analysis, the deviations between REF dataset and test datasets of each single measurement point were exported. Statistical analysis was performed with SPSS 19.0 (SPSS Inc., Chicago, USA).

Results

The positive and negative deviations of average values of the Euclidean distance were calculated and displayed for each group (Fig. 5). Table 1 gives the resulting number of measured points and the calculated divergences after superimposition for all 12 datasets from digitized polyether impressions, indirect digitalisation (Lava Scan ST) and direct digitalisation (Lava C.O.S.).

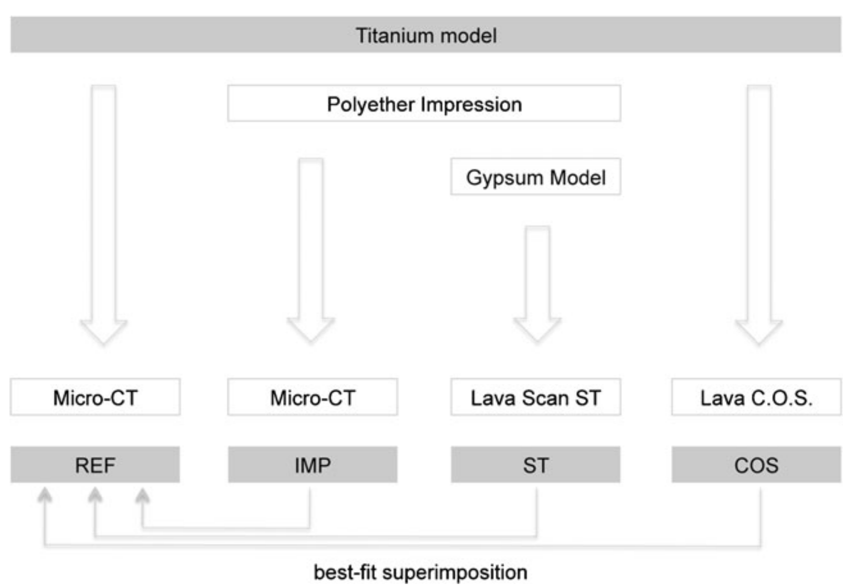

Fig. 1 Overview on the general study procedure and ways of dataset creation based on the titanium model. Twelve datasets per group (IMP 1–12, ST 1–12 and COS 1–12) were superimposed with the reference dataset (REF)

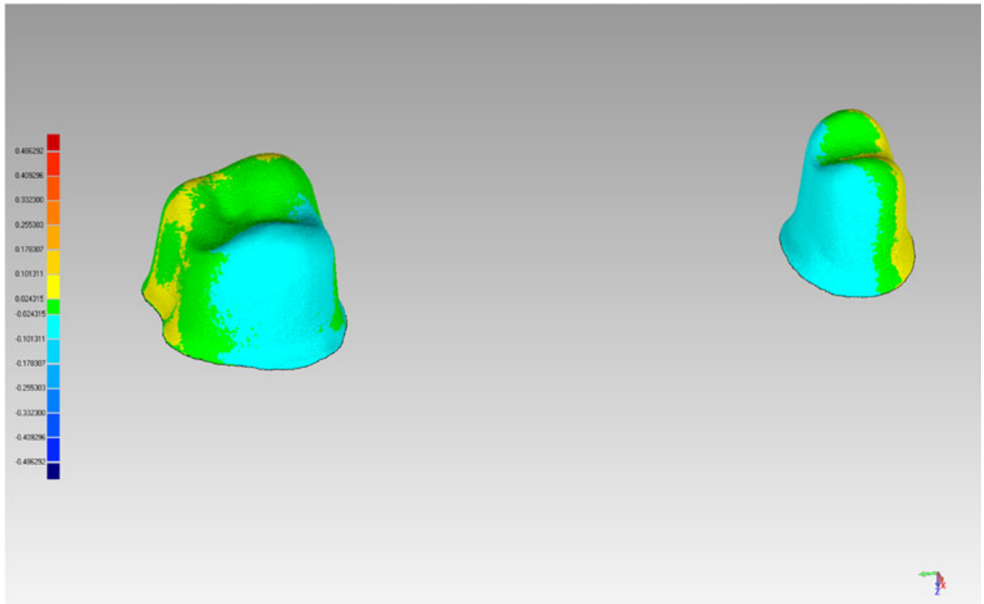

Fig. 2 Deviations after superimposition of REF and IMP datasets displayed in a colour-coded difference image

On the basis of the mean positive and negative deviations and the SD of all 12 datasets from each group, direct digitalisation showed the least deviations (17 μm/−13 μm; SD± 19 μm), followed by digitized polyether impression (23 μm/ −22 μm; SD±31 μm) and indirect digitalisation (36 μm/ −35 μm; SD±52 μm). In terms of averaging maximal positive and negative deviations, polyether impressions showed the highest divergences (457 μm/−691 μm), followed by indirect digitalisation (256 μm/−333 μm) and direct digitalisation (134 μm/−123 μm).

Figure 6 gives the mean absolute values of Euclidean distances, which were calculated by summing up the absolute positive and negative deviations and dividing the result by the number of measured points. Here as well, direct digitalisation showed the least deviations (15 μm; SD± 6 μm), followed by polyether impression (23 μm; SD± 9 μm) and indirect digitalisation of the gypsum cast (36 μm; SD±7 μm).

The Kolmogorov–Smirnov test revealed a normal distribution for mean positive, negative and absolute values in each group. Therefore, the different groups were compared using one-way ANOVA in combination with LSD post hoc test ($p=0.05$). The mean negative and mean absolute values of all groups were statistically significantly different under each other. Comparing the mean positive values of the groups, IMP and COS ($p=0.082$) showed no statistically significant difference, whereas ST and COS, and ST and IMP exhibited statistically significant differences.

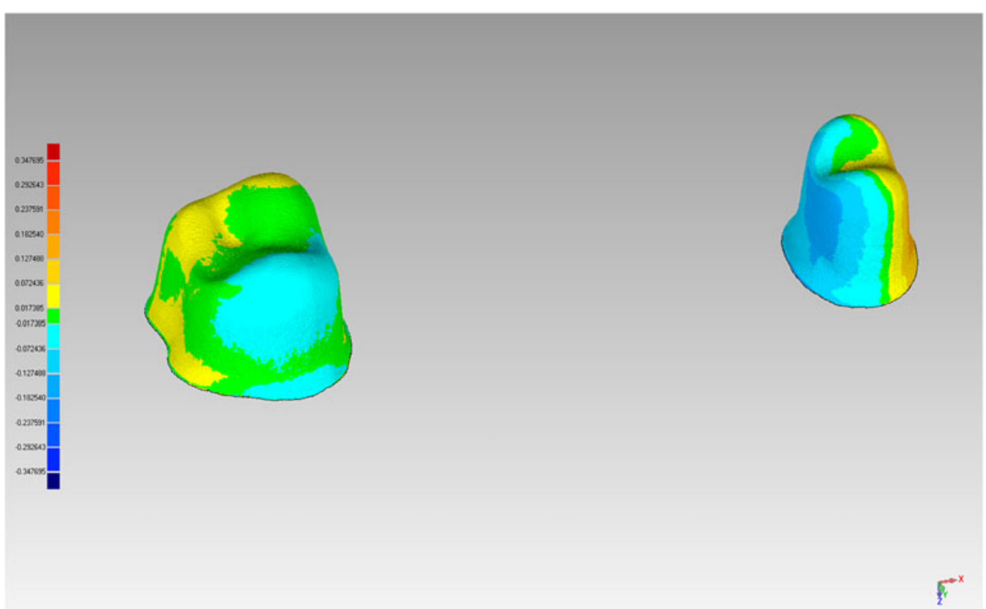

Fig. 3 Deviations after superimposition of REF and ST datasets displayed in a colour-coded difference image

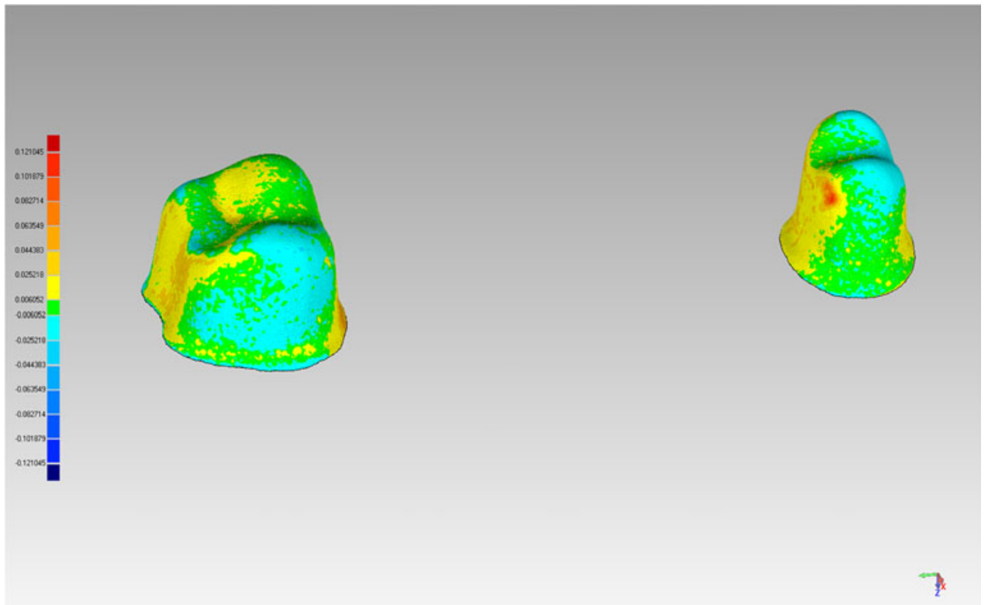

Fig. 4 Deviations after superimposition of REF and COS datasets displayed in a colour-coded difference image

Discussion

Accurate impressions represent an important prerequisite for precise dental restorations. In a survey among 2,000 dental technicians, the problem of impression taking was validated. It was stated that low quality of impressions and insufficient preparations were the greatest obstacles for the production of high-end dental restorations [14]. In this context, intraoral digital data capturing seems to be a logical step to prevent the possible errors already at the very beginning of the digital workflow. However, only insufficient scientific data are available about the accuracy of this new technique.

The aim of this study was to evaluate datasets by superimposition, instead of measuring the entire manufacturing process. This superimposition of test and reference datasets was performed employing a "best fit alignment". Due to the lack of reference shapes, this was the best methodological compromise to obtain the objectives defined in this study. Best fit alignments were already used in several other studies as an approach for 3D dataset comparison [12, 13, 15, 16]. Using this "best fit matching", positive and negative deviations between reference and test objects occur. This makes the interpretation of the results difficult as negative deviations will not occur in the oral cavity when restorations are seated. As well, calculating the arithmetic mean from positive and negative deviations leads to results close to zero and is not displaying the real divergences sufficiently.

The approach employed in the present study uses the mean positive and negative deviations and the standard deviation to estimate the proximity of each test dataset in relation to the reference. From these values, one mean value

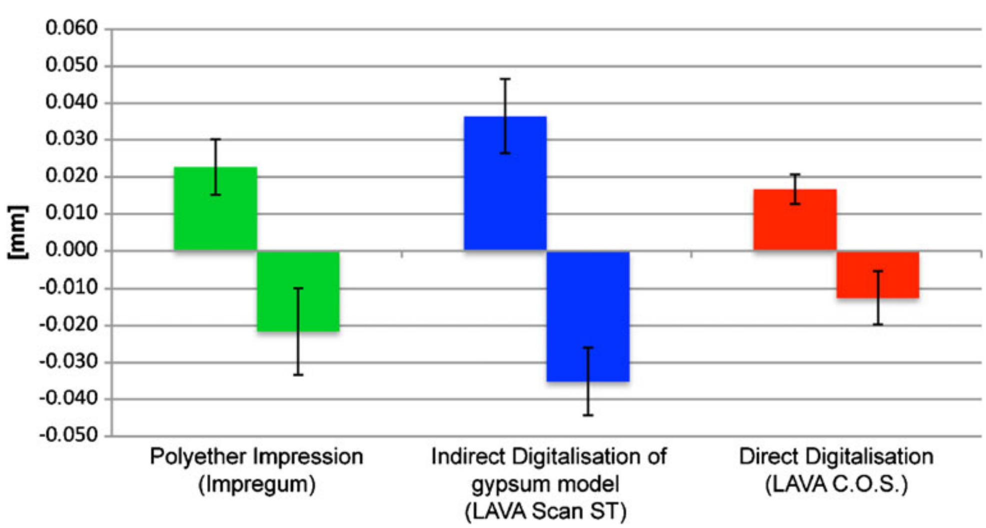

Fig. 5 Mean positive and negative deviations (millimetres) and SD after superimposition of REF dataset with 12 datasets received from each group

Table 1 Results (millimetres) received from superimposition of REF dataset with 12 datasets received from polyether impression (Impregum), indirect digitalisation of the resulting gypsum models (LAVA Scan ST) and direct digitalisation of the titanium model with LAVA C.O.S., respectively

Group		Measured pts.	Max. pos. dev.	Max. neg. dev.	∅ pos. dev.	∅ neg. dev.	SD	∅ abs. dev.
IMP	Mean	410,781	0.457	−0.691	0.023	−0.022	0.031	0.023
	SD		0.453	0.492	0.008	0.012	0.013	0.009
ST	Mean	81,051	0.256	−0.333	0.036	−0.035	0.052	0.036
	SD		0.040	0.026	0.010	0.009	0.010	0.007
COS	Mean	57,633	0.134	−0.123	0.017	−0.013	0.019	0.015
	SD		0.033	0.047	0.004	0.007	0.007	0.006

The table gives the number of measured points, maximal positive and negative deviations, mean positive and negative deviations and the standard deviation (SD) in combination with the mean absolute values of Euclidean distances (millimetres) for each dataset after best fit superimposition with REF dataset

for each group was calculated. The mean positive and negative values for each group could be interpreted as the trueness. However, the values are separated into positive and negative ranges. Since trueness describes the spatial proximity between test object and reference, the average of absolute values of the Euclidean deviation was calculated for each group. This value gives the average distance between test and reference dataset, regarding one single measured point, disregarding whether it is located "over" or "under" the reference surface. This absolute value for one group was interpreted in this study as the trueness of the workflow and digitalisation method, respectively. Direct digitalisation of the titanium model with the Lava C.O.S. scanner showed significantly better trueness than the polyether impression itself and as well as the indirect digitalisation of the referring gypsum cast using the Lava Scan ST.

Dependent on the trueness, the reproducibility of the results was shown by the standard deviation as recommended in ISO Norm 5725–1 [11]. Therefore, the standard deviation can be interpreted as the precision of the single methods; however, the context of the trueness and the repeatability conditions are of major importance. In this context, it seems to be surprising that the SD of average absolute values for IMP is greater than for ST. It might be assumed that the shrinkage of the impression material is compensated by the expansion of the gypsum model. As well, the scanning software might filter out possible outliers and therefore smoothens the surface of the construction datasets. This means that these factors could influence the precision of the single datasets captured.

The higher inaccuracy of the conventional way based on conventional impression, gypsum master cast and extraoral digitalisation can be explained by the numerous potential sources of errors and the long process chain related with that procedure, until a construction dataset is obtained [10, 17, 18]. The reference dataset captured with industrial computed tomography exhibits one million surface triangles and a voxel size of 16.03 µm, which corresponds to an accuracy of about 5 µm.

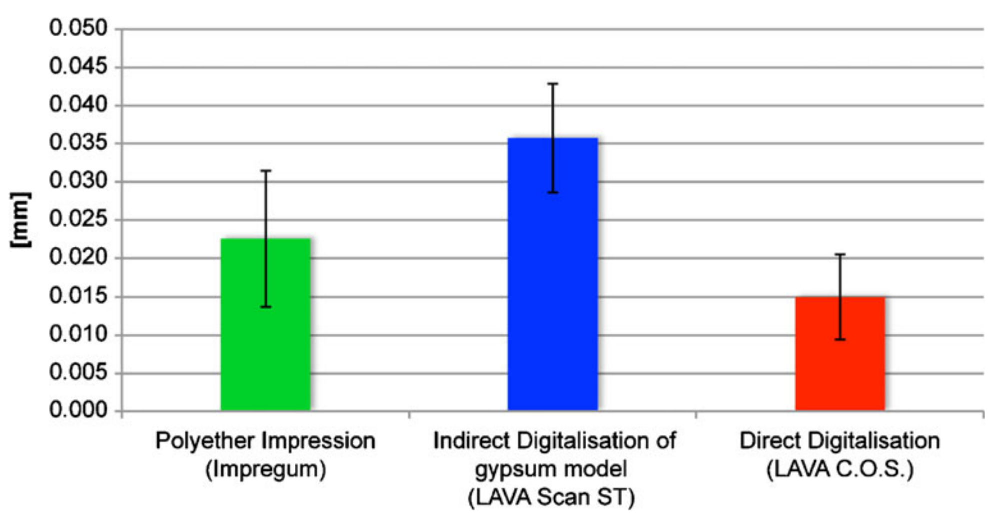

Fig. 6 Mean values and SD of absolute Euclidean distances (millimetres) between the REF dataset and datasets received from polyether impression (Impregum), indirect digitalisation of the resulting gypsum models (LAVA Scan ST) and direct digitalisation of the titanium model with LAVA C.O.S

Another factor influencing the measurement procedure and therefore the results is the process of the superimposition. Pilot tests carried out previously to this study showed a reproducibility of less than 1 μm for the procedure of cutting and alignment of two datasets [19]. These values have to be considered as measuring uncertainty. Thus, it can be assumed that datasets that differ more from the reference than these summed up values are less accurate.

The different approaches of generating STL datasets from the CT and dental scanners, including different ways of postprocessing and filtering of the raw data, can be seen as a limitation of this study. The CT was used as the source for the reference dataset as it exhibits a higher accuracy than the tested dental scanners. As well, the CT technology allows to measure the impression with the same accuracy.

As the postprocessing algorithms used by the dental scanners are not available for the researchers, the possibility to use the same algorithm for the postprocessing of CT datasets was not given. As well, the generation of STL datasets from CT raw data differs a lot from the postprocessing procedure after optical capturing. The aim of the study was the comparison of two ways (direct and indirect digitalisation) of generating datasets for the further design of dental restorations. Both were compared to the same reference dataset, and therefore would include the same measurement error.

Comparing groups COS and ST with group IMP might not lead to misinterpretation as the data of group IMP were not optimized for dental restorations, whereas the postprocessing of group COS and ST was optimized for the further fabrication processes of dental restorations. To compare direct data capturing with the impression itself, the datasets should be both optimized for the fabrication of dental restorations, for example by using the same procedures of postprocessing.

Another point of discussion is the method of interpretation of the divergences after superimposition, to receive values for trueness and precision. Some previous studies use the 80–20 % percentile to interpret the results of best fit alignments, to compensate possible greater inaccuracies when scanning steep areas [13, 15]. As in the present study, the construction datasets, which represent the basis for manufacturing in daily practice, were used for superimposition; the authors decided for another interpretation mode as it is described above. Nevertheless, the present results show the same tendency as a study presented by Ender and Mehl, using the 80–20 % percentile method. When scanning a full arch, the Lava C.O.S. presented better trueness (40.3 μm) and precision values (60.1 μm), compared with Impregum and the referring gypsum cast (55 μm/61.3 μm), but showed no significant difference.

The mode of interpretation of 3D divergences used in the present study has been applied by other authors before. In one in vitro study, direct digitalisation of a gypsum model was carried out using a different system (Cerec 3D) and compared with the conventional procedure and indirect digitalisation. For the prepared single tooth 16 (FDI), the average positive and negative deviations after direct data capturing were 18 μm/−17 μm [16].

For the here applied intraoral scanner LAVA C.O.S., studies evaluating the whole manufacturing process of single crowns are already available. The fit of single crowns from direct and indirect digitalisation using the same systems in vivo as the present study could show statistically significant superior marginal fit of the crowns received from direct data capturing [20]. This supports the idea that a superior digitalisation method leads to superior accuracy of the resulting restorations. The authors are planning a further study, which evaluates the resulting bridge frameworks from the captured datasets in means of internal and external fit to support this thesis.

These in vitro results can give a first hint that direct data capturing technology can offer comparable results like conventional methods. Further in vivo studies must show that this holds true for clinical application as impression procedure and digitalisation are influenced by a variety of factors in the oral cavity. But these studies have to compare the full production process. Besides, the direct feedback in great magnification on the screen displayed directly after intraoral scanning might help dentists to improve their preparations and impressions in the future.

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Conflict of interest The authors declare that they have no conflict of interest.

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