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Influence of material surface on the scanning error of a powder-free 3D measuring system

Michael Kurz · Thomas Attin · Albert Mehl

Abstract

Objectives This study aims to evaluate the accuracy of a powder-free three-dimensional (3D) measuring system (CEREC Omnicam, Sirona), when scanning the surface of a material at different angles. Additionally, the influence of water was investigated.

Materials and methods Nine different materials were combined with human tooth surface (enamel) to create $n=27$ specimens. These materials were: Controls (InCoris TZI and Cerec Guide Bloc), ceramics (Vitablocs® Mark II and IPS Empress CAD), metals (gold and amalgam) and composites (Tetric Ceram, Filtek Supreme A2B and A2E). The highly polished samples were scanned at different angles with and without water. The 216 scans were then analyzed and descriptive statistics were obtained.

Results The height difference between the tooth and material surfaces, as measured with the 3D scans, ranged from 0.83 μm (±2.58 μm) to −14.79 μm (±3.45 μm), while the scan noise on the materials was between 3.23 μm (±0.79 μm) and 14.24 μm (±6.79 μm) without considering the control groups. Depending on the thickness of the water film, measurement errors in the order of 300–1,600 μm could be observed.

Conclusions The inaccuracies between the tooth and material surfaces, as well as the scan noise for the materials, were within the range of error for measurements used for conventional impressions and are therefore negligible. The presence of water, however, greatly affects the scan.

Clinical relevance The tested powder-free 3D measuring system can safely be used to scan different material surfaces without the prior application of a powder, although drying of the surface prior to scanning is highly advisable.

Introduction

Since the introduction of powder-free three-dimensional (3D) measuring systems, many improvements have been made to the technique [1, 2]. Powder-free scanning offers several advantages over powder-based systems, where a powder, consisting mostly of titanium dioxide [3], is sprayed onto a dried tooth prior to scanning. The application of this powder is often deemed unpleasant by both the patient and the attending dentist. Additionally, the measuring process requires great concentration due to the fact that contact with saliva immediately washes the powder away. In addition, difficulties and inaccuracies with the measurement can occur if the spray is overapplied [4]. Therefore, powder-free systems are not only supposed to be more comfortable for the patient but also more user-friendly for the dentist. It has also been claimed that when using a powder-free system, the camera lens is less prone to soiling, there is no need to avoid touching the powdered surfaces, and it is not always necessary to have a dental assistant present [1]. Scanning with a powder-free 3D measuring unit is clinically successful and powder-free 3D oral scans produce good values that are reliable and precise, in particular, for single-tooth scans [5].

The powder is used to create a dental surface of the same color and opacity but without any reflections. This was a precondition for the application of the 3D measuring devices used for intraoral scanning until 2006, when the first powder-free

M. Kurz (✉) · T. Attin · A. Mehl
Clinic of Preventive Dentistry, Periodontology, and Cariology,
Division of Computerized Restorative Dentistry, Center of Dental
Medicine, University of Zurich, Plattenstrasse 11,
8032 Zurich, Switzerland
e-mail: michael.kurz@uzh.ch

3D measuring system was launched [6]. In general, a patient can have restorations fabricated from different materials in his or her oral cavity, including composites over glass ionomer cements, ceramics, and metals. Each of these materials has a unique translucency. The translucency of a material can be described as the amount of light that the material allows to pass through, while the remainder of the light is reflected or absorbed [7]. In other words, translucency is a material property that corresponds to partial opacity or that state between complete opacity and complete transparency [8].

Digital intraoral measuring devices use light to record intraoral surfaces. The 3D measuring device used in this study (CEREC Omnicam, Sirona, Bensheim, Germany) calculates values by applying an active triangulation method. An optical setup emits light of different wavelengths in stripe patterns, which are reflected by the intraoral surfaces and then recorded by a charge-coupled device (CCD) chip. The angle-related position shift between the emitted and returned light is then calculated by applying triangulation to give the third dimension. When using the CEREC Omnicam, only a single scan with a short exposure is necessary to acquire a three-dimensional image. The speed of this process eliminates the problem of camera shake and allows the use of a free-flowing imaging technique [2].

To measure the surface data with the triangulation method, the reflected light has to be captured at the triangulation angle from a precisely defined surface area. First, however, this is only possible if the reflected light is diffused, which is not the case with glossy surfaces having specular properties. Light rays striking such surfaces are reflected according to their angle of incidence, which makes it difficult for the camera to calculate three-dimensional data using the triangulation method. Second, the translucency of a material affects the way that the light is reflected. As the translucency of a material increases, more light is absorbed until the relevant portion of the light is reflected. The different translucencies of dental materials have been investigated by several studies using the translucency parameter (TP) [9–19]. In all of the referenced studies, the TP was determined by measuring the values for lightness (L*), red green chromatic coordinates (a*), yellow blue chromatic coordinates (b*) over W background (values determined using a white background), and background (B; values determined using a black background) and then substituting them into the following equation:

$$ TP = \left[(L_W - L_B)^2 + (a_W - a_B)^2 + (b_W - b_B)^2 \right]^{1/2} $$

As the translucency of a material increases, so also does its TP. The TP is closely correlated in inverse proportion to the thickness of the sample [9, 10, 13, 15, 20]. Furthermore, the shade of a material can lead to its having a different TP [10,

11, 14, 21]. The translucency of enamel is always higher than that of dentine [9, 14]. Ryan et al. [14] showed that composite materials with a shade of A2 are more translucent than dentine. A study comparing different CAD/CAM ceramics showed that the TP of ceramics [19] is either about the same or slightly higher than that of enamel with dentine and/or dentine itself [9]. In contrast, the TP of metallic dental restorations is 0. The light emitted by the camera is immediately reflected by metallic surfaces, but penetrates translucent materials differently depending on their translucency until it is ultimately reflected. Enamel, for instance, allows light to penetrate more deeply than dentine.

Whenever a powder has to be applied before initiating a digital impression, the operator of the 3D measuring device has to ensure that there is no saliva on the area to be scanned. Since saliva immediately washes away the powder, the occurrence of wetting can easily be recognized. In contrast, without powdering or matting, moistened surfaces with saliva, especially in the distal regions, are not as easily detectable. Therefore, those companies offering powder-free 3D measuring devices suggest blow-drying the teeth prior to scanning. Light is refracted differently by the surface of a liquid, which tends to lead to inaccuracies in a digital impression.

Therefore, this study sets out to investigate the following questions:

(1). How is the height measurement of a triangulation scan affected by the surface and transparency of a material?
(2). How does noise in a scan vary with the surface of the material?
(3). How does the height measurement of a scan depend on the thickness of any fluid film?

This study involved performing in vitro scans using a powder-free 3D measuring device (CEREC Omnicam, Sirona) on different dental materials. Additionally, water was applied to the specimens to simulate the effect of saliva, after which possible errors in the measurement were again evaluated.

Materials and methods

Specimen preparation

Ten extracted, noncarious, upper jaw human molars were each cut four times (on the buccal, palatal, mesial, and distal sides; Fig. 3) by using a milling unit (IsoMet® low-speed saw, Buehler, Düsseldorf, Germany) into 2-mm (±0.1 mm) slices to create n=27 specimens. Each specimen consisted of up to one half human tooth (enamel on the surface and dentine underneath) and one half of the following dental materials (Table 1): unsintered zirconium dioxide ceramic as a *positive control* (PC; InCoris TZI 55/19, Sirona); a highly translucent

Table 1 Material groups, type of material, number (*N*) of specimens per material, number (*N*) of scans per test series (TS), product name, and manufacturer of material bonded to human tooth, PC was scanned in extraoral mode (e) and in intraoral mode (i)

Material group	Material	*N* specimens	*N* scans (TS I)	*N* scans (TS II)	Product name	Manufacturer
Control	Positive control (PC$_e$&$_i$)	3	36	–	InCoris TZI 55/19	Sirona (Bensheim, Germany)
	Negative control (NC)	3	18	–	Cerec Guide Bloc	Sirona
Ceramic	Ceramic 1 (VM)	3	18	12	Vitablocs® Mark II	Vita (Bad Säckingen, Germany)
	Ceramic 2 (EM)	3	18	–	IPS Empress CAD	Ivoclar Vivadent (Schaan, Lichtenstein)
Composite	Composite 1 (TC)	3	18	12	Tetric Ceram A2	Ivoclar Vivadent
	Composite 2 (FB)	3	18	–	Filtek™ Supreme XTE Universal Composite A2B	3 M ESPE (Seefeld, Germany)
	Composite 3 (FE)	3	18	–	Filtek™ Supreme XTE Universal Composite A2E	3 M ESPE
Metal	Amalgam (AM)	3	18	–	Dispersalloy®	Dentsply (York, PA, USA)
	Gold (AU)	3	18	12	Modulor®	Cendres+Métaux (Biel, Switzerland)

material as *negative control* (NC; Cerec Guide Bloc, Sirona); two *glass ceramics*, namely, a *leucite-reinforced glass-ceramic* (EM; IPS Empress CAD, Ivoclar Vivadent, Schaan, Lichtenstein) and a *feldspar ceramic* (VM; Vitablocs® Mark II, Vita, Bad Säckingen, Germany); three *composites* (TC, FB, and FE; Tetric Ceram, Ivoclar Vivadent, Filtek™ Supreme XTE Universal Composite A2B, 3 M ESPE, Seefeld, Germany and Filtek™ Supreme XTE Universal Composite A2E), as well as two *metal alloys*, namely, a *gold alloy* (AU; Modulor®, Cendres+Métaux, Biel, Switzerland) and *amalgam* (AM; Dispersalloy®, Dentsply, York, PA, USA; Table 1).

The color A2 (VITA classical Shade Guide, Vita) was chosen for all the composites and ceramics used in the study. The Cerec Guide Bloc was chosen as the negative control because of its high, glass-like translucency, whereas the unsintered zirconium dioxide ceramic was used as a positive control as it has near-zero translucency, comparable to that of plaster.

The PC, NC, VM, EM, and AU specimens were also cut into 2-mm (±0.1 mm) slices using another cutting unit (Micracut® 150 precision cutter, Bursa, Turkey).

The four ceramic samples (NC, PC, VM, and EM) were silicatized and silanized. The tooth samples, however, were pretreated with a three-step adhesive system (Syntac Classic, Ivoclar Vivadent). Subsequently, the tooth and ceramic samples were cemented together using a universal dual-curing cement (Variolink Ultra, Ivoclar Vivadent).

Before applying the TC, FB, and FE composites, the tooth specimens were again pretreated with the three-step adhesive system (Syntac Classic, Ivoclar Vivadent).

The AU specimens were also silicatized and silanized. The corresponding tooth samples were pretreated with a two-step adhesive system (ED Primer A+B, Kuraray, Tokyo, Japan) and then cemented to the AU by using a dual-curing resin cement (PANAVIA™ 21, Kuraray).

Subsequently, the bonded specimens (PC, NC, VM, EM, TC, FB, FE, and AU) were embedded in a sample holder with a diameter of 8.5 mm (Figs. 1, 2, and 3) using denture resin (Paladur®, Heraeus Kulzer, Hanau, Germany).

An exception to the above was the AM specimen. The tooth specimen was embedded in the sample holder with denture resin (Paladur®, Heraeus Kulzer). Subsequently, undercuts were made to assist with retention before placing the AM filling.

To create a flat surface on the surface of the specimen, especially the transitional area between the tooth and the adjacent material, each specimen was placed on a polishing machine (Planopol-2, Struers, Willich, Germany) with microgrit sandpaper (ISO/FEPA Grit designation P2500). To better initiate the powder-free 3D measuring camera (CEREC Omnicam, Sirona), a custom-made ring with a surface

Fig. 1 Specimen embedded in sample holder and surrounded by custom-made ring with surface structure
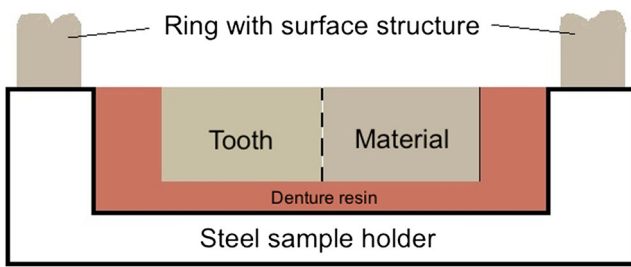
Fig. 2 Schematic of cross-section of the specimen embedded in the sample holder

structure was designed using the CEREC SW 4.2 software and milled using a polymethyl methacrylate (PMMA) block (Telio CAD, Ivoclar Vivadent). This was mounted on the sample holder around the specimen with Super Glue (Sekundenkleber, Orbis Dental, Münster, Germany; Figs. 1 and 2). Between the optical impression cycles, each specimen was kept stored in water.

Digital impression

A digital optical impression was taken using a 3D powder-free intraoral camera (CEREC Omnicam, Sirona) and the CEREC SW Version 4.2 software. Each scan was saved in .stl format.

Test series I

Each specimen was dried before scanning. For each specimen, three intraoral mode (i) scans were taken at an angle of 90° to the surface, followed by three further scans at an angle of 45°. One exception to this was the PC group, for which the samples were supplementary, scanned three times in extraoral mode (e). The specimen holder was placed on a tray and rotated through 360° about its axis during the measurement process, which took about 20 s/scan.

Test series II

Three specimens (VM, TC, and AU), one of each of the material groups, were chosen to determine whether different water levels influence the accuracy of the digital impression. First, 150, 200, and 250 μl of tap water were applied to the specimen using a 1,000-μl pipette (Pipetman Classic P1000, Gilson, Middleton, WI, USA). This corresponded to a calculated water height of 2,100, 2,900, and 3,300 μm. On each of these water levels of the sample, a scan was performed while holding the camera at a 45, 60, and 90° angle to the specimen's surface using an adjustable camera holder to determine whether variations in the angle lead to particular errors in the
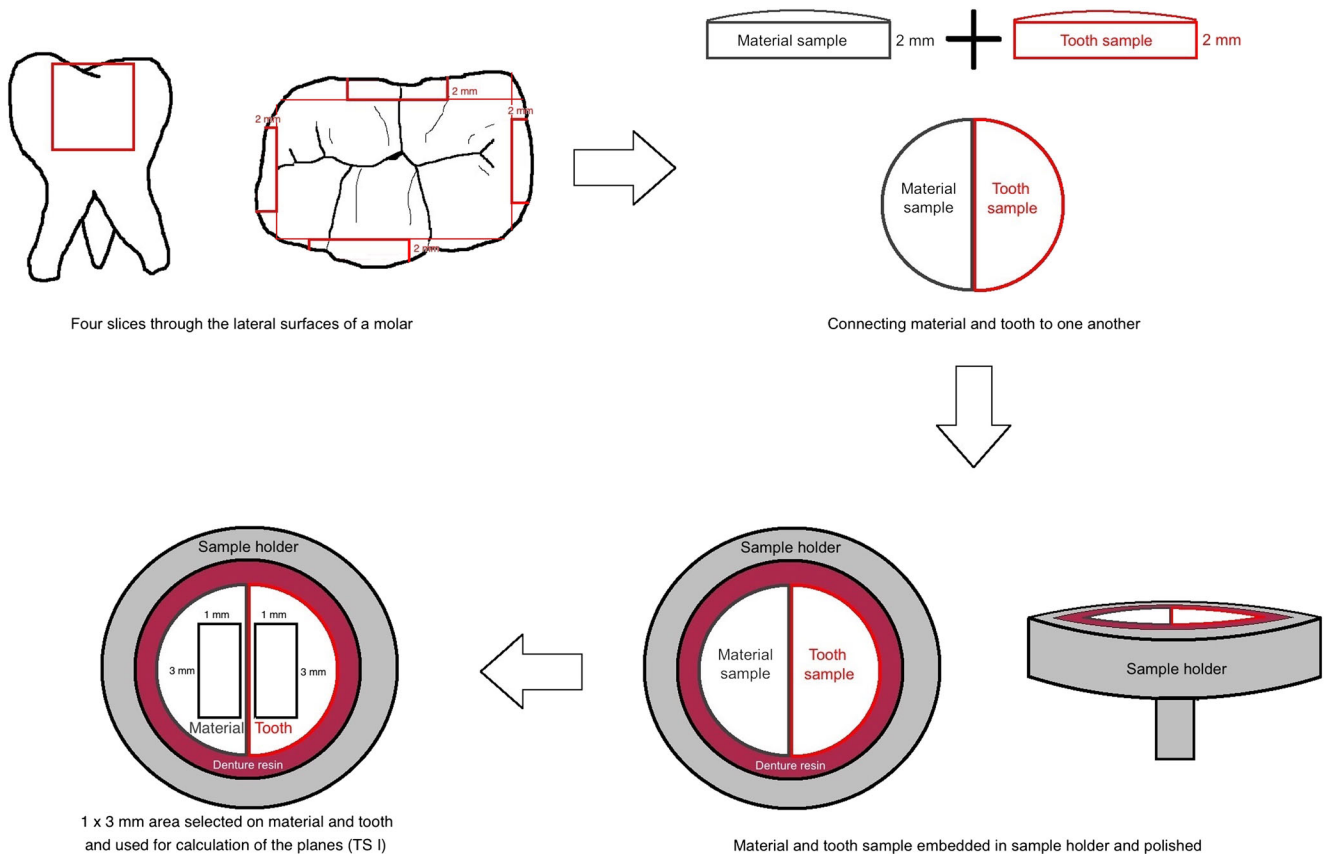

Fig. 3 Schematic of the preparation of the samples

measurement. A scan of each specimen was also performed without water, again at a 45, 60, and 90° angle to the specimen's surface to serve as a control group. The adjustable camera holder was set to the corresponding angle using a geometer and was then manually moved back and forth for about 20 s.

Digital evaluation

The evaluation of the different scans was performed using surface analysis software (Match3D 2.5, Germany) [22].

Test series I

Using the test series I data, we performed a statistical analysis of possible noise on the enamel or material samples and also calculated detected height differences between the enamel and material. Always an area of 1×3 mm near the junction was selected on the tooth and on the test material (Fig. 3) and used for calculation of the regression plane. The distance of each measured point to the regression plane was calculated, and from that, the 10 and 90 % percentiles were determined. The average value on the z axis of this plane was set to zero. Subsequently, this region of interest was selected so that the mean z value and the 10th and 90th percentile deviation could be determined. The same procedure was applied to the material surface.

Test series II

To determine whether there were any differences in the height measurements with different water levels and camera angles, the Match3D software was used to overlap the water-free control scan with the corresponding scan taken with water, for a given angle. This was done by aligning the custom-made ring with the surface structure in the scans of the water-free and irrigated samples. The differences between the scans with and without the water could be quantified and used for statistical analysis by recording and averaging the difference value of a slice drawn through the difference image. A larger difference corresponded to a greater deviation between the irrigated scan and the water-free scan.

Statistical analysis

The data sets were analyzed and descriptive statistics were extracted by using PASW Statistics (Version 18, SPSS, Chicago, IL, USA). For test series I, the height difference was calculated as the difference between the z values of the centers of adjacent regression planes, and its mean and standard deviation was evaluated and analyzed. Error bar diagrams were drawn up to graphically illustrate the height differences between the materials and the tooth surface to which they were attached. The noise for each material was defined as the

difference between the 90th and 10th percentile, divided by 2 [(90th percentile−10th percentile)/2]. The mean and standard deviation of these values were then calculated for each group. For test series II, the mean and standard deviation values were calculated for the superimposed water-free and irrigated sample scans. The mean values of the standard deviation between the dry and irrigated samples were calculated by averaging the values for each material tested (VM, TC, and AU) and each angle at which a scan was taken.

Results

Test series I

The measured mean (M) height difference between the tooth and material surface is shown in Fig. 4. This figure also shows the standard deviation (SD) for angles of both 90 and 45°. The ceramic material groups (VM and EM) exhibit the smallest deviation relative to the enamel. The mean height difference between the ceramics and the tooth surface is, for VM, $M_{VM45°}=$ 2.38 μm (±2.27 μm) and $M_{VM90°}=0.83$ μm (±2.58 μm) and, for EM, $M_{EM45°}=1.97$ μm (±11.09 μm) and $M_{EM90°}=1.07$ μm (±4.40 μm). The height difference for the composite group is greater than that for the ceramic group. In particular, the more translucent FE exhibits a greater negative height difference between the tooth and the material surface of $M_{FE45°}=-14.79$ μm (±3.45 μm) and $M_{FE90°}=-11.57$ μm (±4.92 μm). The height difference is less for body-colored composite TC, for which $M_{TC45°}=-5.17$ μm (±6.92 μm) and $M_{TC90°}=-7.72$ μm (±3.91 μm), and FB, for which $M_{FB45°}=-8.00$ μm (±4.96 μm) and $M_{FB90°}=-9.93$ μm (±2.49 μm). The metallic groups, consisting of AM and AU, exhibit a greater positive height difference, with mean values for AM of $M_{AM45°}=$ 14.47 μm (±9.11 μm) and $M_{AM90°}=11.39$ μm (±5.22 μm) while for AU, $M_{AU45°}=11.28$ μm (±8.57 μm) and $M_{AU90°}=13.03$ μm (±4.82 μm).

The noise for the tooth surface ranges from 4.55 μm (±1.18 μm) to 9.41 μm (±4.72 μm) (Table 2), while the noise for the materials ranges from 3.23 μm (±0.79 μm) to 14.24 μm (±6.79 μm) (Table 3). These figures do not take the control group into consideration.

The noise is higher for certain materials especially when scanned at a 45° angle. In particular, samples of the metal group (AM and AU) exhibit a higher level of noise of $M_{AM45°}=12.6$ μm (±6.42 μm) and $M_{AU45°}=14.24$ μm (±6.79 μm) when scanned at a 45° angle. When scanning at a 90° angle, these noise values are reduced by about half (Table 3). The values of the noise on the tooth and the material are either about the same or smaller when scanned at 90° instead of at 45° (Tables 2 and 3).

Several exceptions are apparent in the control group. For the tooth samples, a very high noise value of $M_{NC45°}=39.64$ μm

Fig. 4 Error bar diagram of mean height difference (±SD) between the materials (PC, EM, TC, FB, FE, AM, and AU) and the tooth
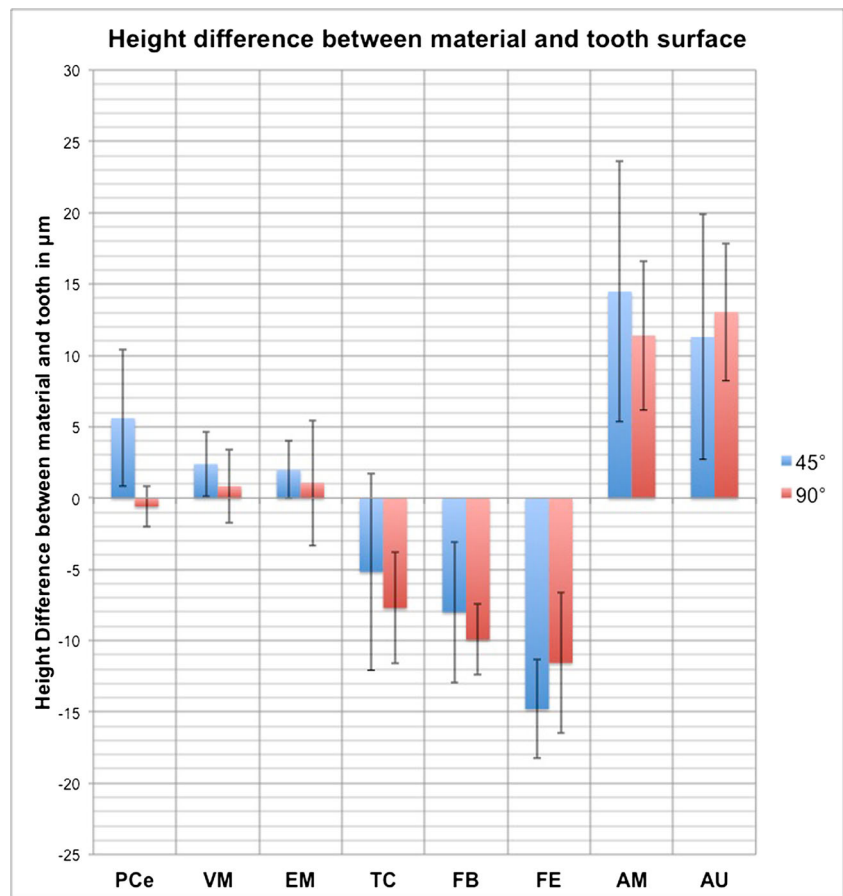
(± 29.62 μm) is apparent when scanned at a 45° angle. Within the control group, high noise values of $M_{PCi45°} = 61.78$ μm (± 18.38 μm), $M_{PCi90°} = 110.18$ μm (± 30.85 μm), $M_{NC45°} = 243.28$ μm (± 128.37 μm), and $M_{NC90°} = 22.25$ μm (± 15.02 μm) can be seen when scanned in intraoral mode.

The noise values for PC_i are the exception as they become smaller when the sample is scanned at a 45° angle. The noise within the PC scans can be reduced to values of $M_{PCe45°} = 9.09$ μm (± 13.97 μm) and $M_{PCe90°} = 2.64$ μm (± 0.68 μm) when scanned in extraoral mode (Table 3).

Table 2 Noise as 10th to 90th percentile with standard deviation (SD) on tooth sample connected to different materials (all values in micrometer)

Tooth	45° Angle		90° Angle	
	Noise$_{45°}$	SD$_{45°}$	Noise$_{90°}$	SD$_{90°}$
PC$_e$	7.35	3.54	5.01	1.43
PC$_i$	7.47	2.73	8.75	3.19
NC	39.64	29.62	7.89	3.37
VM	7.50	2.53	5.31	1.44
EM	7.05	2.51	6.60	4.46
TC	7.94	3.66	7.43	1.75
FB	6.12	1.89	4.55	1.18
FE	6.92	1.28	6.23	2.00
AM	9.41	4.72	6.02	2.50
AU	7.69	3.63	6.33	2.32

Table 3 Noise as 10th to 90th percentile with standard deviation (SD) on each material connected to a tooth (all values in micrometer)

Mat.	45° Angle		90° Angle	
	Noise$_{45°}$	SD$_{45°}$	Noise$_{90°}$	SD$_{90°}$
PC$_e$	9.09	13.97	2.64	.68
PC$_i$	61.78	18.38	110.18	30.85
NC	243.28	128.37	22.25	15.02
VM	4.15	1.39	3.88	1.07
EM	7.85	3.89	3.23	.79
TC	4.05	1.15	5.04	2.63
FB	3.81	1.32	3.99	2.27
FE	6.24	3.09	5.52	2.19
AM	12.60	6.42	6.77	2.05
AU	14.24	6.79	7.69	2.36

Table 4 Mean and standard deviation (SD) values of deviations when scanned at a given angle and with a given water level on VM, TC, and AU specimen

	Mean (±SD) [μm] at 2,100 μm			Mean (±SD) [μm] at 2,900 μm			Mean (±SD) [μm] at 3,300 μm		
	VM	TC	AU	VM	TC	AU	VM	TC	AU
45°	806.58 (±58.65)	1,237.00 (±15.99)	971.09 (±36.33)	1,524.24 (±51.34)	1,504.16 (±13.06)	1,272.06 (±42.50)	1,529.68 (±42.26)	1,627.23 (±97.25)	1,369.01 (±57.59)
60°	547.91 (±41.82)	816.30 (±11.47)	637.17 (±29.62)	992.32 (±40.45)	983.35 (±28.71)	848.32 (±34.93)	1,246.74 (±50.43)	1,139.24 (±71.64)	1,004.10 (±42.83)
90°	400.61 (±21.85)	475.02 (±6.77)	395.75 (±16.36)	601.91 (±9.27)	594.66 (±2.62)	652.87 (±3.76)	648.32 (±9.70)	655.48 (±5.01)	716.24 (±2.79)

Test series II

A deviation between those scans with different amounts of water (150, 200, and 250 μl) and the corresponding control scans without water can be seen, regardless of whether they are scanned at an angle of 45, 60, or 90° (Table 4). The measurement errors range from approximately 300 to 1,600 μm.

The mean deviations of each material and the standard deviation for test series II are shown for the ceramic group represented by VM, for the composite group represented by TC, and for the metallic group represented by AU in Table 4.

All the deviations for all the scanned materials (VM, TC, and AU) increase with higher water levels and lower scanning angles (Table 4). For example, VM with a water height of 2, 900 μm exhibits a deviation relative to the scan performed without water of 1,524.24 μm (±51.34 μm) when scanned at a 45° angle, 992.32 μm (±40.45 μm) when scanned at a 60° angle, and 601.91 μm (±9.27 μm) when scanned at a 90° angle.

Discussion

3D measuring devices are gaining popularity because of their ability to scan surfaces without the need for preconditioning. However, many studies have shown that the accuracy and precision of digital impressions, such as those for complete-arch dental impressions, are not yet as accurate as conventional impressions taken with a vinyl siloxanether material, but the difference is now relatively small [5]. The trueness values for complete-arch digital impressions are for the CEREC Omnicam (Sirona)=37.3 μm (±14.3 μm), the CEREC Bluecam (Sirona)=29.4 μm (±8.2 μm), the iTero (Align Technology, San Jose, CA, USA)=32.4 μm (±7.1 μm), and the Lava COS (3 M ESPE, St. Paul, MN, USA)=44.9 μm (±22.4 μm) [23]. Values for a single-tooth scan taken with 3D measuring devices show an even higher accuracy [24–28, 23], while the accuracy of a conventional impression can vary between 10 and 70 μm depending on the material used or the study [29, 30, 25, 31].

This study primarily examined, if powder-free systems are dependent upon different material surfaces at all and if it is at all possible to scan the different materials in an appropriate

quality. Furthermore, systems based on the triangulation method should show the most significant errors concerning these aspects, because, e.g., the penetration depths within materials and the refraction of light in water films is theoretically more influenced than with scanners based on the principles of confocal microscopy and time-of-flight methods due to the different pathways of the rays (principles are described in more detail, e.g., in Logozzo et al. [32]). In a first approach, that was the reason for investigating only one system, which is based on the triangulation method.

The results of the present study show that height differences arise between the scanned tooth and the corresponding material in test series I. Because the tooth surface is used as a reference to evaluate the height difference to various materials, this study does not show the trueness of the scan of the material itself. However, these values show that they may have no clinical relevance because even the largest deviations, as measured for the FE, AM, and AU samples, are well within the range of inaccuracies produced by conventional impressions. This means that the fitting of a reconstruction should not be influenced by systematic errors arising from the material surfaces.

The mean height differences measured for test series I have the same order as the translucency of the materials (TP: metallic dental restorations<enamel/dentine≈ceramics<composites [9, 19, 14]). This phenomenon could be explained by assuming that the light being output by the powder-free 3D measuring device penetrates materials with different TPs differently until its maximum intensity is reflected and once again captured by the camera of the measuring device. To obtain standardized evidence, color A2 was chosen for all materials. The teeth were also chosen by not using too light or dark shades. An unsintered zirconium dioxide ceramic was selected as a positive control since it has an opaque surface.
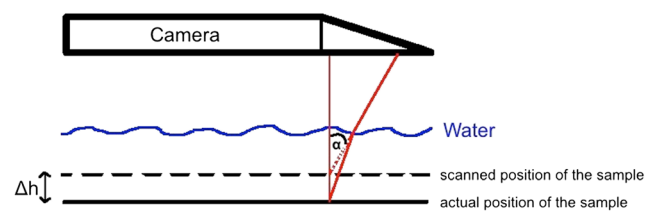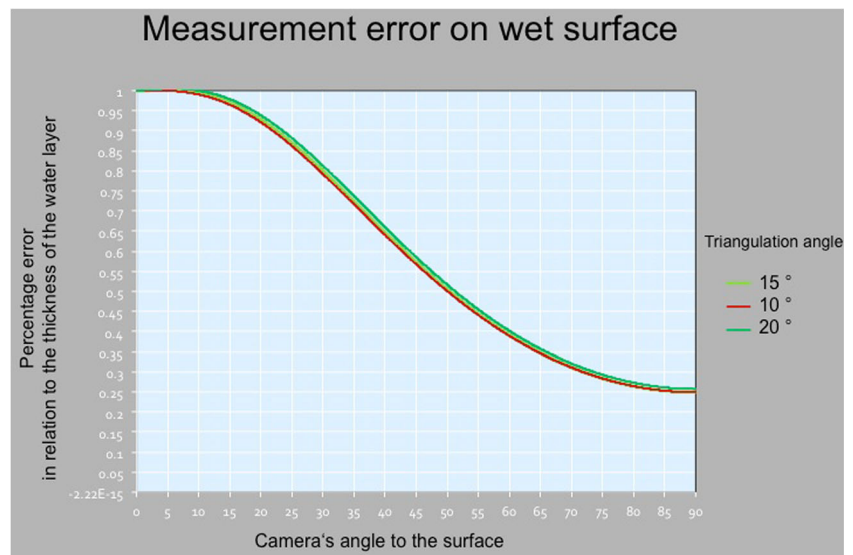

Fig. 5 Illustration of error in measurement (Δh) with the camera triangulation angle (α)

The 3D measuring system used might not have the appropriate settings to scan surfaces with a diffuse scattering in intraoral mode, while these surfaces appear to be accurately scanned in the extraoral mode. This incidental finding leads to a limitation in this study but is of minor importance, as an additional negative control gave good results.

Furthermore, this study showed that the scanning of well-dried samples gives more reproducible results when the samples are scanned at an angle of 90°. On certain materials, mainly the highly reflecting metal groups (AM and AU), a higher level of noise is apparent when they are scanned at an angle of 45°. The noise level was reduced significantly when the camera was held vertically to the sample instead of being tilted at a 45° angle. However, the noise on the materials, which can be found intraorally as dental restorations, is also clinically negligible under the limitations of this study.

The results obtained for test series II show that there are major deviations when water is applied to the samples before scanning. This can be explained by the refraction of light in the water. This leads to a deviation in the angular measurement and, therefore, to a shift in the obtained height values (Fig. 5). The powder-free 3D measuring system used in this study emits light that is reflected by the structure being scanned and which is then again captured by the camera at a different angle to the light that was emitted. This angle is called the "triangulation angle." The triangulation angle of the CEREC Omnicam (Sirona) is around 8°. Figure 6 shows a theoretical calculation of this effect, indicating how the deflection changes with the camera angle. Using this figure, errors in the measurement can be estimated. A water film of 100 μm scanned at a 65° angle with a 10° triangulation angle would lead to a measuring error of 35 %, in this example of 35 μm. The lowest measuring error of about 25 % can always be reached by scanning at a 90° angle. This calculation roughly matches the results obtained for test series II. The amount of water applied to the samples was determined as follows: The minimum amount of water necessary to wet the entire sample was applied (2,100 μm) so as to avoid surface tension effects. The maximum water height of 3,300 μm was determined because of irregularities in the framework of the custom-made ring. The ring's surface structure is such that its diameter increases as more water is added. This explains the differences between the calculated and actual measurement errors, especially those seen in the scans taken with a water height of 3,300 μm.

The results obtained for test series II show that it is clinically relevant to completely remove any water, in the form of saliva, prior to scanning with a powder-free 3D measuring systems. This, of course, is no different to most 3D measuring systems [33] or conventional impressions [34].

Conclusions

Within the limitations of this study, the following main conclusions could be drawn:

(1). The use of different dental materials gives rise to height differences in the scans, but are within an acceptable range for the clinically relevant procedures.
(2). Noise on the materials is also within an acceptable range for clinically relevant procedures and can be decreased by holding the camera as close to perpendicular to the sample as possible, rather than at a 45° angle.
(3). Water on the samples can lead to errors in measuring the height of surfaces. These values are clinically relevant and point to the desirability of ensuring dry conditions prior to scanning with the investigated powder-free 3D measuring device, in order to acquire accurate digital intraoral scans.

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

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