

Accuracy and precision of 3 intraoral scanners and accuracy of conventional impressions: A novel in vivo analysis method

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ABSTRACT

Objective: To evaluate a novel methodology using industrial scanners as a reference, and assess in vivo accuracy of 3 intraoral scanners (IOS) and conventional impressions. Further, to evaluate IOS precision in vivo.

Methods: Four reference-bodies were bonded to the buccal surfaces of upper premolars and incisors in five subjects. After three reference-scans, ATOS Core 80 (ATOS), subjects were scanned three times with three IOS systems: 3M True Definition (3M), CEREC Omnicam (OMNI) and Trios 3 (TRIOS). One conventional impression (IMPR) was taken, 3M Impregum Penta Soft, and poured models were digitized with laboratory scanner 3shape D1000 (D1000).

Best-fit alignment of reference-bodies and 3D Compare Analysis was performed. Precision of ATOS and D1000 was assessed for quantitative evaluation and comparison. Accuracy of IOS and IMPR were analyzed using ATOS as reference. Precision of IOS was evaluated through intra-system comparison.

Results: Precision of ATOS reference scanner (mean 0.6 μm) and D1000 (mean 0.5 μm) was high. Pairwise multiple comparisons of reference-bodies located in different tooth positions displayed a statistically significant difference of accuracy between two scanner-groups: 3M and TRIOS, over OMNI (*p* value range 0.0001 to 0.0006). IMPR did not show any statistically significant difference to IOS. However, deviations of IOS and IMPR were within a similar magnitude. No statistical difference was found for IOS precision.

Conclusion: The methodology can be used for assessing accuracy of IOS and IMPR in vivo in up to five units bilaterally from midline. 3M and TRIOS had a higher accuracy than OMNI. IMPR overlapped both groups.

Clinical significance: Intraoral scanners can be used as a replacement for conventional impressions when restoring up to ten units without extended edentulous spans.

1. Introduction

CAD/CAM was introduced in dentistry for single-unit restorations over thirty years ago, and advancements in technology has made it possible to produce complex multi-unit restorations on teeth and implants [1–4]. An essential part of the workflow was the indirect digitization process by laboratory scanners of gypsum models poured from traditional analogue impressions [5]. Parallel to this technology, CEREC, a commercialized intraoral scanner (IOS), made it possible to digitize the dental status in situ [6,7]. However, the early CEREC IOS were limited to single-tooth restorations and came as an integral part in a proprietary workflow accompanied by an in-house milling machine.

Since the late 2000's, there has been a rapid increase in the number of commercial IOS with scanners capable of capturing full dental arches [8]. Yet, with an open platform allowing for third-party CAD/CAM

manufacturing, and rapid growth in the number of IOS, there is limited data to validate if IOS can replace conventional impressions.

Varying terminology exists in the science of metrology for explaining intra- and inter-system variations. Although some research groups in dental literature have used the ISO 5725 [8–14], this study has adopted the more common definition of accuracy and precision. Hence, accuracy being defined as the ability of a measurement to match the actual value, and precision defined as the ability of a measurement to be consistently reproduced.

Several in vitro studies have evaluated IOS applying methodology of 3D Compare Analysis based on varying software best-fit alignment, ranging from single-units to full dental arches [5,8–12,15]. Some studies comparing IOS and conventional impressions have found IOS to demonstrate a statistically significant lower accuracy [11,12]. However, variations in study design, execution and material properties pose

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a challenge in comparing results between existing studies, even when conducted under optimal conditions and far from clinical reality. A study by Muller et al. [16] found different scanning strategies amongst IOS to result in statistically significant differences in accuracy. Gimenez et al. [17] found differences due to bias when comparing scans from experienced and inexperienced users scanning implant models.

Material properties and scanner technology can further affect IOS accuracy. Nedelcu and Persson [15] found sizeable differences in non-coating scanners and Li et al. [18] have shown that increased translucency in scanned objects resulted in lower accuracy. Yet several studies evaluating IOS in vitro have used a variety of materials, from gypsum [19], and polyurethane [9], acting as almost perfect diffusers, to metal [11], having a higher level of specular reflection. These material properties differ greatly from naturally translucent teeth, and may either oversimplify the clinical reality of non-coating scanners, or contrarily put the non-coating scanners to great disadvantage when scanning metal.

Models with translucency and refraction index close to enamel and dentin [15], have been adopted by Renne et al. [8] in vivo. Yet, there are other properties beyond translucency, such as opacity, iridescence, surface gloss, and fluorescence which vary individually between human teeth, as does the effect of tooth age, thickness and color of the enamel and underlying dentin [20]. Any in vitro model will further be limited compared to clinical reality as the models will not take into account non-attached tissues, such the sulcus, lips, floor of the mouth or tongue. IOS use pattern recognition to stitch multiple images with partial overlapping areas into full models [15], and the scans will, voluntarily or not, include a certain amount of data of non-attached tissues. Any movement between measurements in the underlying surfaces may cause improper stitching of the scan. These are elements that are practically impossible to model in vitro.

There are few in vivo studies of IOS. Ender et al. [13,14], focused on the precision of numerous intraoral scanners and conventional impressions in quadrant and complete-arch impressions. The studies do not take into consideration the accuracy of each system.

A novel approach to evaluating accuracy of IOS and conventional impressions in vivo was conducted by Kuhr et al. [21], utilizing a reference-system based on bonded spheres onto teeth and a custom transfer guide. However, as the accuracy analysis is only made at the location of the spheres, there is limited possibility in evaluating accuracy of any surface deviations beyond the spheres, or to assess the in vivo precision of the transfer guides used to attach the bonded spheres.

This pilot study is the first to assess accuracy intraorally using an industrial grade scanner as a reference with accuracy and precision beyond that achievable with IOS or conventional impressions. It is not limited to the subject's dentate situation and can depict the full buccal surface, which makes it possible to visually evaluate variations in accuracy beyond the reference-bodies in the transfer method [21]. The aim of this pilot study was to evaluate the methodology, where accuracy of IOS and conventional impressions could be analyzed. Further, to assess precision of intraoral scanners in vivo.

The null hypotheses were firstly that the reference scanner would demonstrate negligible intra-system deviations, thus displaying a high precision and allowing the scanner to be used as a reference scanner. Secondly, that the laboratory scanner would show similar negligible intra-system deviations. Thirdly, that accuracy between IOS and conventional impressions, and fourthly, that precision of IOS systems would show no statistically significant differences.

2. Materials and methods

2.1. Subject characteristics and treatment

Five subjects with referrals for implant treatment of a missing first or second premolar in the upper jaw participated in the study after informed consent and ethics approval (Dnr 2015/324; Regional Ethical

Review Board, Uppsala). The inclusion criteria were no other missing teeth with residual spacing in the premolar to premolar area. Upon 12 weeks healing of implant surgery with two different diameters, (4 x RP 4.3 and 1 x NP 3.75, Nobel Parallel CC; Nobel Biocare AB, Gothenburg, Sweden), healing abutments (4 x RP and 1 x NP, both 5 mm diameter; Nobel Biocare AB), were removed and scan-bodies were connected to the implants and hand-tightened, (4 x Elos Accurate Intra Oral 2A-B Scan Body, 1 x Elos Accurate Intra Oral 2A-A Scan Body; Elos Medtech, Gothenburg, Sweden).

2.2. Scans

Subjects were positioned in an operating chair raised at 30° angle with the head and neck fixated using an orthopedic vacuum pillow (223940000; Camp Scandinavia AB, Helsingborg, Sweden). The chair was stabilized with dorsal supports to eliminate movement.

Clear self-retractors were placed (Adult Self Retracting; Photomed, Van Nuys, USA) to create a clear and dry field of view. Four reference-bodies in the shape of hemispheres in Alumina (Al₂O₃) with refraction index 1.72, (Goodfellow, Huntingdon, UK), milled to 3 mm in diameter, (Kullberg Mikroteknik AB, Lycke, Sweden), were bonded with light-curing luting cement, (Variolink Esthetic LC; Ivoclar Vivadent, Schaan, Lichtenstein) and LED cured, (Bluephase Style; Ivoclar Vivadent) to primarily the buccal enamel of laterals and second premolars in the upper jaw. However, adaptations had to be made due to anatomical and physical variations, and the reference-body was shifted in three cases unilaterally. In one case the reference-body was bonded to the first molar positioned in the space of a missing second premolar. In a second case, the reference-body was bonded to the first premolar as the second premolar was the actual implant position. In the third case, the reference-body was bonded to a central incisor, as the lateral was fully restored in porcelain. The reference-bodies were numbered as position one to four from right premolar (Pos. 1), via right lateral (Pos. 2), left lateral (Pos. 3) to left premolar (Pos. 4).

The teeth were carefully air-dried and a light coating layer was administered (CEREC Optispray; Sirona, York, USA). To evade excessive coating beyond the teeth of the upper jaw, an anterior and occlusal contrast, (Anterior Contrast and Occlusal Contrast; Photomed, Van Nuys, USA) was used to physically block coating particles from unnecessarily adhering to retractors, soft-tissues, and opposing dentition.

An industrial-grade scanner, ATOS Core 80 5MP, with software and manufacturer details listed in Table 1, was mounted on a proprietary tripod on stable concrete flooring, to eliminate any micromovements due to vibrations during scanning sequences. The scanner unit was calibrated and tested according to VDI/VDIE 2634 (VDI e.V.; Düsseldorf, Germany), displaying maximum deviations: 1 µm probing error form (sigma), -4 µm probing error (size), 2 µm sphere spacing error and - 3 µm length measurement error. The scanner was used to scan the subjects' upper jaw, and due to the natural curvature of the jaw, each scan consisted of 5–7 successful sequences. The scan commenced

Table 1
Reference scanner and intraoral systems, manufacturer, software versions and acquisition technology.

System	Manufacturer	Software	Light Source	Color
ATOS Core 80 5MP	GOM, Braunschweig, Germany	Pro 8.1	Blue Light	Monochrome
3M True Definition	3M, St. Paul, USA	2.0.2.0	LED	Monochrome
Omniscam (CEREC)	Sirona, York, USA	4.3	LED	Generic color
Trios 3	3Shape, Copenhagen, Denmark	1.3.4.5	LED	True to color



Fig. 1. View of tripod-mounted ATOS reference scanner and attached retractors in one subject, enabling an eccentric scan of the coated upper jaw and bonded reference-bodies.

in the midline and subsequently moved laterally and posteriorly by positioning the target field in the view-finder of the stereo camera, with at least fifty percent overlapping the previous sequence. Several sequences were automatically discarded due to software warnings of movement during the sequence scan. Reference stickers normally, applied outside the scanning area to assist the transformations of each sequence in the ATOS system, could not be used due to the need for coating and the risk of displacement due to poor adherence. Therefore, transformations relied on best-fit-alignment of overlapping sections. Due to anatomical limitations, it was not possible to capture data posteriorly of the second premolar in some subjects. The setup of ATOS, coated reference-bodies and retractors can be seen in Fig. 1.

Coating was removed using rigorous water spray and microbrushes, (Quick Stick microbrushes; Dentonova AB, Stockholm, Sweden) and retractors were detached. Subjects were asked to rinse with water, and after a fifteen-minute recess, allowing for rehydration of teeth, the scan-body was removed and re-attached. Soft retractors were placed, (Optragate; Ivoclar Vivadent) to allow for a dry operating field. The upper jaw was scanned three times with each IOS per manufacturer protocol in the following order: Trios 3 (TRIOS), CEREC Omnicam (OMNI), and 3M True definition (3M), the latter after coating with proprietary spray applicator, (3M Powder Sprayer; 3M, St. Paul, USA), (Table 1). As the 3M scanner required coating, the order of scanning was maintained as removal of all coating was considered an absolute necessity between scanners. After finalizing scans with IOS, the coating from 3M was removed using water spray and teeth were cleaned with microbrushes before removing soft retractors. Minor coating particles were allowed in non-essential areas. Scan-bodies were replaced with

hand-tightened impression copings for open tray (4 x RP CC and 1 x NP CC; Nobel Biocare AB) and one impression (IMPR), (Impregum Penta Soft; 3M, St Paul, USA) in a tray, (Position Tray; 3M, St. Paul, USA) with cut-out for the impression pin, was carried out on each subject.

The impressions were disinfected (MD 520; Dürr Dental AG, Bietigheim-Bissingen, Germany) according to manufacturer's recommendation, and gently air-dried. Impressions were poured between 24 and 48 h with type IV dental stone (Fujirock EP; GC Europe, Leuven, Belgium). All impressions prior to pouring and subsequent gypsum models were stored at room-temperature (+20 to +22 °C) for 24 h. An appropriate sized scan-body was re-attached to the model analogue and hand tightened. Each model was scanned three times with D1000 laboratory scanner, (D1000; 3Shape, Copenhagen, Denmark).

2.3. Processing scan-data and analysis

All non-essential data, such as traces of retractors, soft tissues or opposing dentition, were manually removed in all ATOS sequences to only include buccal scan data of teeth and scan-bodies.

The resulting scans were polygonised in the software with settings at high detail to create an STL file.

STL files were exported from all IOS and the dental laboratory scanner. 3M files were acquired from the 3M Online Case Manager and specific proprietary dental laboratory software was used to export STL files from OMNI, (InLab 15; Sirona), and both TRIOS and D1000 dental laboratory scanner, (Dental System 2015; 3Shape).

The ATOS reference-files, IOS files and D1000 laboratory scans of gypsum models were imported into 3D inspection and metrology software, (Geomagic Control 2015; Geomagic, North Carolina, USA). IOS files were manually cropped to remove all soft-tissues. For subsequent calculation of accuracy and precision, and after best-fit alignment based on the manual selection of the four reference-bodies excluding interfering peripheral bonding material, a 3D Compare Analysis was performed. Manual surface annotations of 2 mm diameter were selected on the top cap of the reference-bodies for deviation measurements and statistical analysis. Color histograms were included to visualize the distribution of deviations of the surfaces with settings at nominal $\pm 20 \mu\text{m}$ and critical $\pm 100 \mu\text{m}$.

The use of reference-bodies for best-fit alignment over full surface match was preferred as scan acquisition was optimized for the reference-bodies regarding coating as well as angle of acquisition. Furthermore, intra-subject measurement annotations from each reference-body were gathered consistently.

2.4. Precision evaluation of ATOS reference-scanner and D1000 laboratory scanner

The three ATOS reference-scans acquired from each subject were cross-compared. Similarly, the three scans with D1000 dental laboratory scanner of one gypsum model per subject, were cross-compared.

2.5. Accuracy evaluation of IOS scans and conventional impression

The first ATOS reference-scan of each subject, (ATOS S1), was used to assess accuracy within each IOS scanner group: 3M, OMNI, and TRIOS. Accuracy was evaluated for IMPR, based on the first D1000 laboratory scan, (D1000 S1).

Initial investigations of scatterplots in R [22] showed that non-negligible correlation was present between measurements from two positions, and hence a bivariate response had to be considered. Moreover, the variability on an individual basis implied that a random-effects model was necessary. This was managed by fitting a random-effects model with a bivariate response; one regressor in the form of the factor describing the system and a random-effect variable. The model was fitted by the routine lme in the R package nlme [23]. Multiple comparisons were carried out by routines in the R package

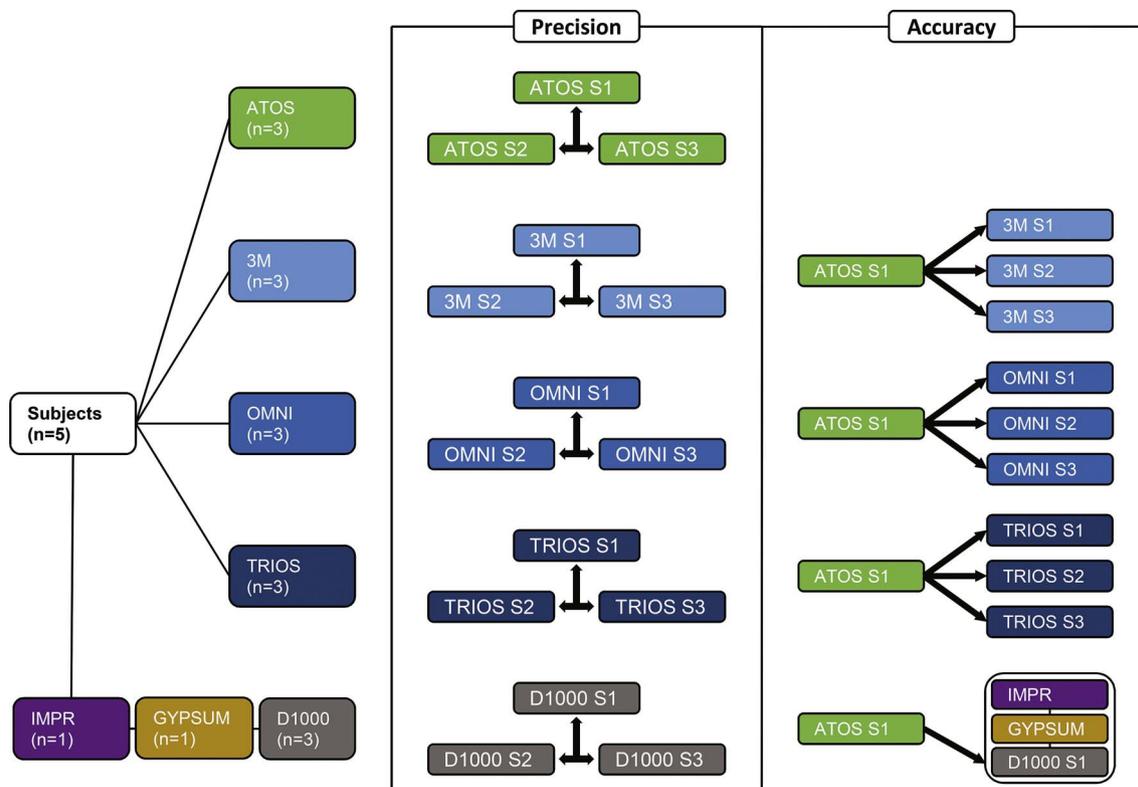


Fig. 2. Flow-chart of scans with ATOS reference-scan, IOS and impression for each subject, cross-comparison for precision and use of reference for accuracy test. Multiple intra-system scans are denoted by S1, S2 and S3.

multcompView [24]. Residuals of the fitted model were investigated by plotting and the fitted models were considered adequate. Significance level was set at $p = 0.05$.

2.6. Precision evaluation of IOS scans

The three IOS-scans for 3M, OMNI, and TRIOS, were cross-compared.

Fig. 2 shows a schematic overview of the protocol, and subsequent accuracy and precision tests.

3. Results

3.1. Precision evaluation of ATOS reference-scanner

Fig. 3 shows the cross-3D Compare Analysis of ATOS reference-scanner in one of the five subjects. The overall deviations were a mean of $0.6 \mu\text{m}$, median of $0.5 \mu\text{m}$, minimum of $-4.0 \mu\text{m}$ and maximum of $+4.8 \mu\text{m}$, and thus well below nominal ($\pm 20 \mu\text{m}$). The color histogram displays a consistent spike in line with the numeric results. Careful examination of the surfaces showed minor artefacts that appeared consistent between the three scans from each subject (i.e. buccal surface of right canine).

3.2. Precision evaluation of D1000 laboratory scanner

Fig. 4 shows a cross-comparison deviation analysis based on D1000 for each subject. Deviations were nominal, with a mean of $0.5 \mu\text{m}$, median of $0.9 \mu\text{m}$, minimum of $-1.7 \mu\text{m}$ and maximum of $+4.8 \mu\text{m}$. The precision was in a similar range to the ATOS reference scanner used in vivo, with a consistent spike in distribution in the histogram. Only minute negative artefacts could be noticed, believed to be trapped air when fabricating the gypsum model (incisal edge, right lateral and left central).

3.3. Accuracy evaluation of IOS scans and conventional impression

Results after applying a random-effects model shows IOS and IMPR to be of significance in all pair-wise comparisons, (p values: Pos. 1 & 4 = 0.0006, Pos. 2 & 3 = 0.0001, Pos. 1 & 2 = 0.0001, Pos. 1 & 3 = 0.0006, Pos. 2 & 3 = 0.0001, Pos. 2 and 4 = 0.0001, Pos. 3 & 4 = 0.0001). Pairwise, multiple comparisons show group inclusion of 3M and TRIOS in one group, whilst OMNI forms a separate group. IMPR shows inclusion in both the 3M and TRIOS group, as well as the OMNI groups.

Fig. 5 visualizes a representative result of one such scan through 3D Compare Analysis.

Fig. 6 plots pair-wise accuracy measurements, mean, median and confidence interval in all scans for Pos. 1 and Pos. 4. Similarly, Fig. 7 plots pair-wise data for Pos. 2 and Pos. 3.

Visual analysis and plots confirm the findings of most posterior deviations in the OMNI group reaching a higher positive deviation, thus equaling an expanded area, whilst frontal deviations appear negative, equaling a contracted area. Although IMPR shows similar patterns, there were overlaps with both the 3M/TRIOS group and OMNI group.

3.4. Precision evaluation of IOS scans

Results after applying the random-effects model after pair-wise deviation comparison of reference-body positions show no statistical significance, (p values: Pos. 1 & 4 = 0.23, Pos. 2 & 3 = 0.39, Pos. 1 & 3 = 0.23, Pos. 2 & 4 = 0.23).

Figs. 8, 9 and 10, show representative results from cross-3D Compare Analysis of the three IOS systems in one subject. Although intra-system deviations vary in magnitude, it is evident that deviations are most pronounced in the molar areas.

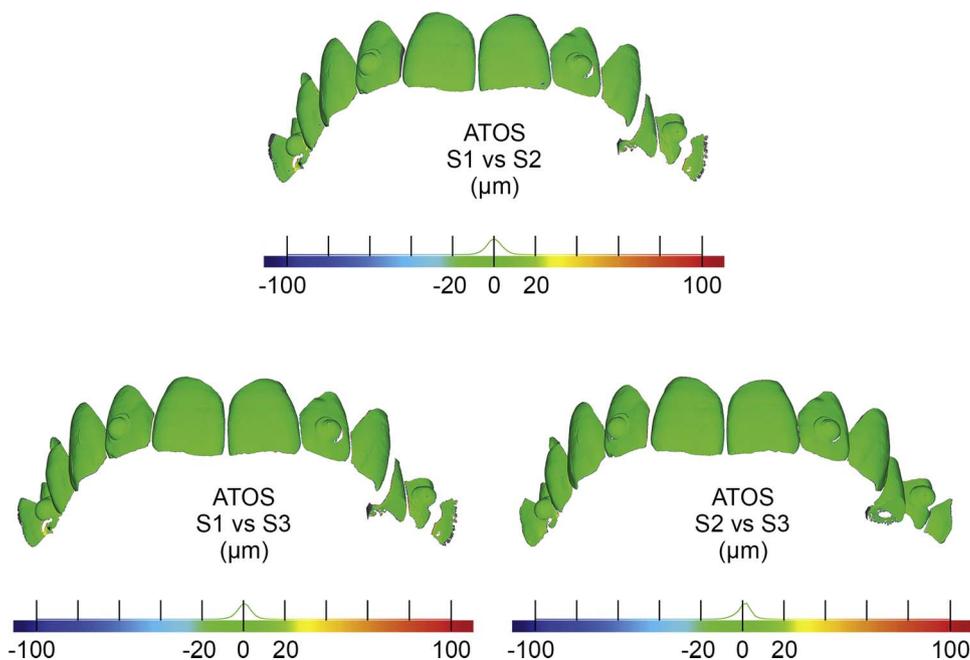


Fig. 3. Precision of ATOS reference-scan with cross-comparison for one subject. Color histogram depicting deviations with settings at nominal $\pm 20 \mu\text{m}$ and critical $\pm 100 \mu\text{m}$.

4. Discussion

The results support the primary and secondary null hypothesis, as intra-system variations of ATOS and D1000 were deemed clinically negligible and in the same range. The study rejected the third hypothesis, that no significant differences exist among IOS and conventional impressions. The fourth hypothesis, that there were no statistically significant differences between IOS regarding precision, was upheld.

4.1. Precision evaluation of ATOS reference-scanner

This pilot study has been preceded by testing of multiple scanning protocols and equipment to increase repeatability and the understanding of existing limitations. The results from the ATOS system indicate a precision of at least an order of magnitude over that of IOS.

However, the ATOS industrial measuring system is not originally intended for clinical applications and did have certain limitations.

Firstly, all the conducted scans were done in the upper jaw of each subject with the head and neck fixated using a vacuum pillow to minimize any movement during scans. Although care was taken not to disperse the coating unintentionally to retractors, lips or opposing dentition, unintended coating of surfaces were registered in each sequence to some extent. Involuntary micro movement of the lips and other areas with residual particles during the short sequence scan was believed to be the cause for multiple sequences being automatically discarded. After manually removing non-essential areas, there appeared to be no effect from movement in the precision validation.

Secondly, to successfully scan the surfaces, coating had to be applied. Preliminary tests revealed that the highly controllable battery-operated powder sprayer used for the 3M IOS, did not allow for proper scanning with ATOS. It is unclear whether this was due to coating

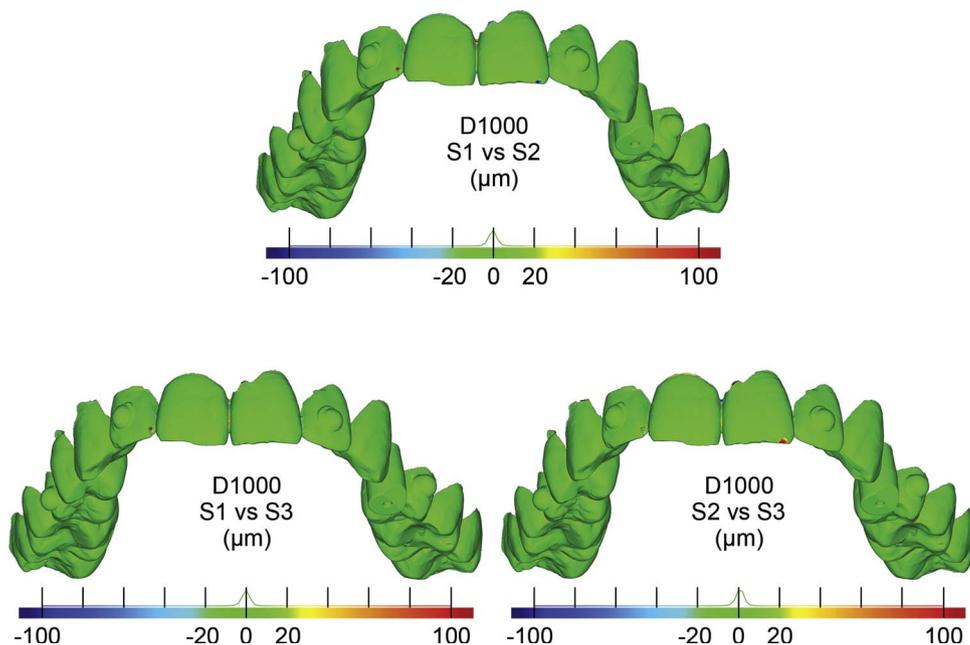


Fig. 4. Precision of D1000 laboratory scanner with cross-comparison for one underlying impression and gypsum model. Color histogram depicting deviations with settings at nominal $\pm 20 \mu\text{m}$ and critical $\pm 100 \mu\text{m}$.

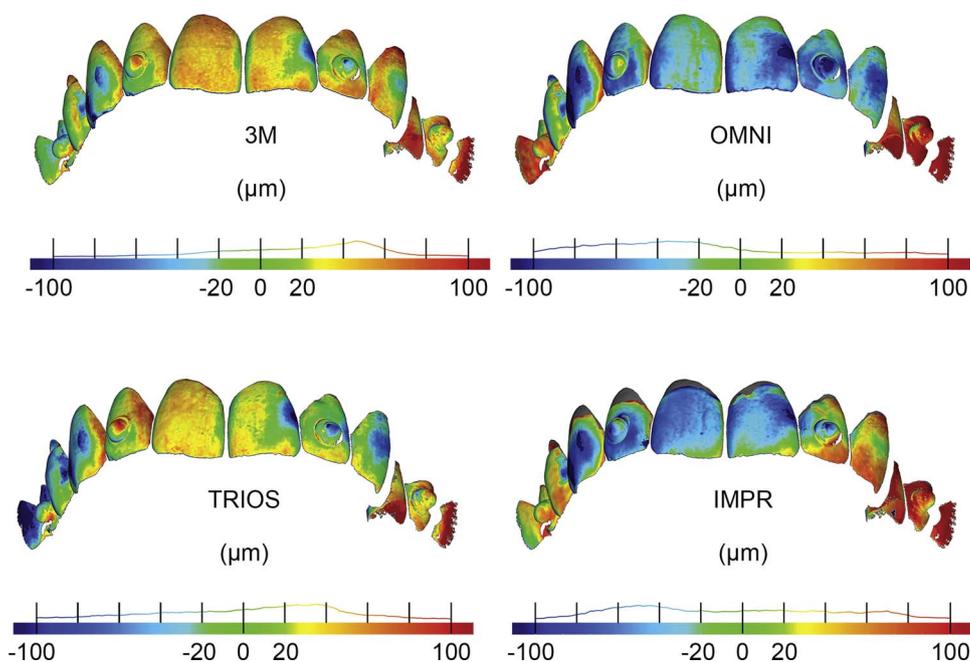


Fig. 5. Selected representative 3D Compare Analysis of IOS and IMPR and color histogram depicting deviations with settings at nominal $\pm 20 \mu\text{m}$ and critical $\pm 100 \mu\text{m}$.

composition or a resulting lower particle density. Thus, a less controllable coating administration with pressurized canister had to be used, (CEREC Optispray; Sirona). Although previous studies have shown no significant difference between excessive and normal coating of IOS using the battery-operated sprayer over a full preparation scan [15], the same may not apply for the reference-scanner when using a pressurized canister.

Though great care was taken in dispersing the coating primarily onto scan-bodies, some localized artefacts on the buccal surfaces could be identified when comparing outcome of accuracy measurements between IOS. It is believed that those artefacts, not visible upon clinical inspection, were caused by an uneven coating build-up when attempting to coat the reference-bodies evenly. It may be possible to achieve a greater homogeneity in coating thickness by using paintbrush

technology used in vitro measurements, but no such system is available for clinical use. However, the precision of the ATOS was concluded to be noteworthy high and in line with the D1000 scanner and the accuracy seen in the ATOS VDI/VDE 2634 pre-testing. Due to a somewhat greater uncertainty regarding areas outside the reference-bodies, and in order to increase the measurement repeatability, the best-fit alignment was conducted using the reference-bodies.

4.2. Precision evaluation of D1000 laboratory scanner

The D1000 laboratory scanner shows results which are in line with ATOS reference scanner. But unlike the ATOS system, the D1000 works under optimal conditions. No test was done to evaluate the accuracy, but the precision is notably high and exceeds that of IOS systems. Other

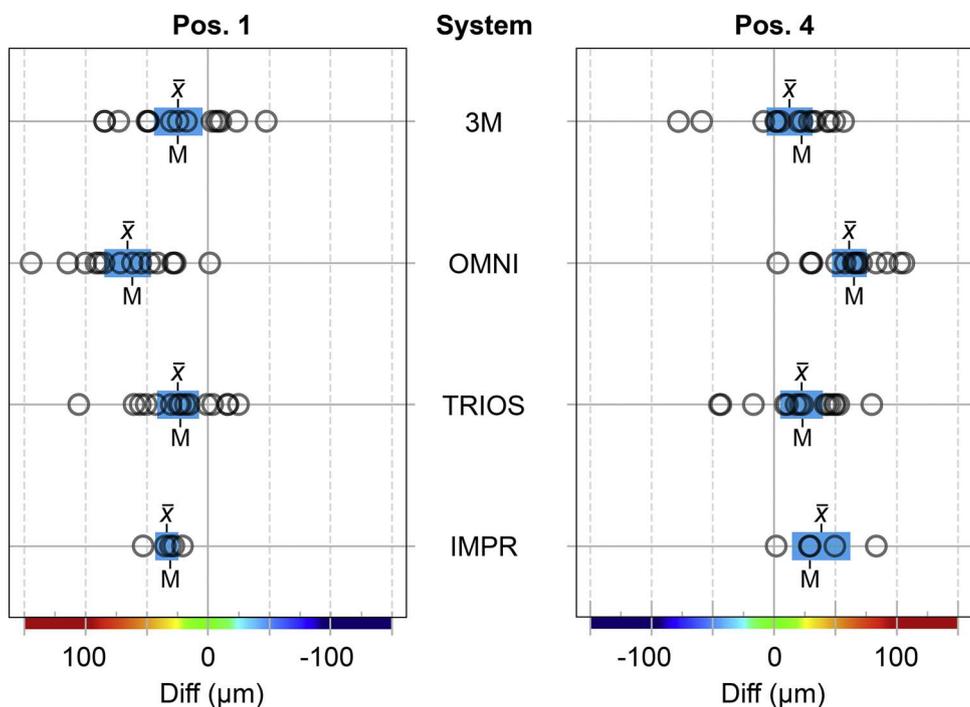


Fig. 6. Accuracy plotting and statistical data for mean value (\bar{x}), median (M) and confidence interval at 95% (blue bar) of IOS and IMPR in Pos. 1 (right premolar) and Pos. 4 (left premolar) with reversed x-axis for Pos. 1. A Positive or negative deviation denoting an expanded or contracted model versus the reference scan.

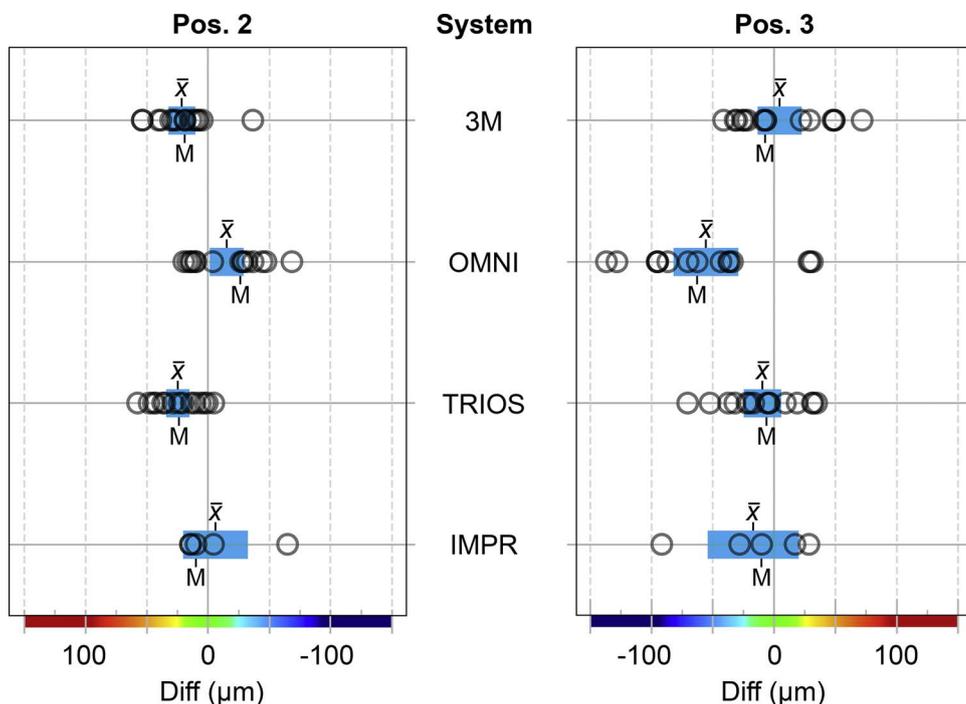


Fig. 7. Accuracy plotting and statistical data for mean value (\bar{x}), median (M) and confidence interval at 95% (blue bar) of IOS and IMPR in Pos. 2 (right incisor) and Pos. 3 (left incisor) with reversed x-axis for Pos. 2. A Positive or negative deviation denoting an expanded or contracted model versus the reference scan.

factors regarding the analogue impression-taking and pouring of model may thus be of greater impact regarding the precision in the full indirect digitization workflow.

4.3. Accuracy evaluation of IOS scans and conventional impression

Accuracy of IOS showed inter-system variations that were of statistically significant difference. All scanners displayed posterior deviations, however, a clear trend were bilateral positive deviations in the premolar area of OMNI and negative deviations in the frontal area. Similar results can be seen in the IMPR, though not to the same extent. Thus, 3M and TRIOS formed a clear separate group with higher accuracy compared to OMNI. IMPR showed an overlap of both groups. This finding is conclusive for both statistical and visual analysis. Although

not using the same analysis method, Kuhr et al. [21] found IMPR to have the highest accuracy, followed by 3M and TRIOS. OMNI on the other hand displayed the lowest accuracy in vivo, which is in line with the findings in this study, and similarly with Patzelt et al. [9] in vitro. These studies differ from results found in vitro by Ender et al. [11], where OMNI displayed higher accuracy than other IOS.

4.4. Precision evaluation of IOS scans

Although, statistical analysis did not show any differences of precision, visual analysis displayed varying deviations predominantly in the posterior areas with obvious flaring. Although scans were performed by an operator with previous clinical experience in all three IOS systems, the precision analysis further fuels questions of which part of

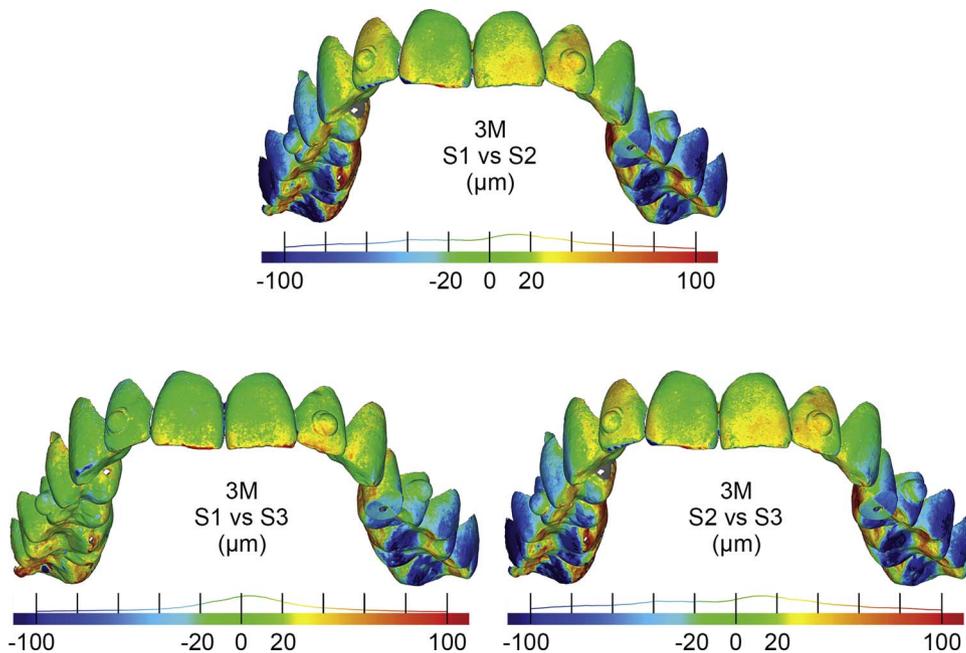


Fig. 8. Precision of 3M IOS with cross-comparison for one subject. Color histogram depicting deviations with settings at nominal $\pm 20 \mu\text{m}$ and critical $\pm 100 \mu\text{m}$.

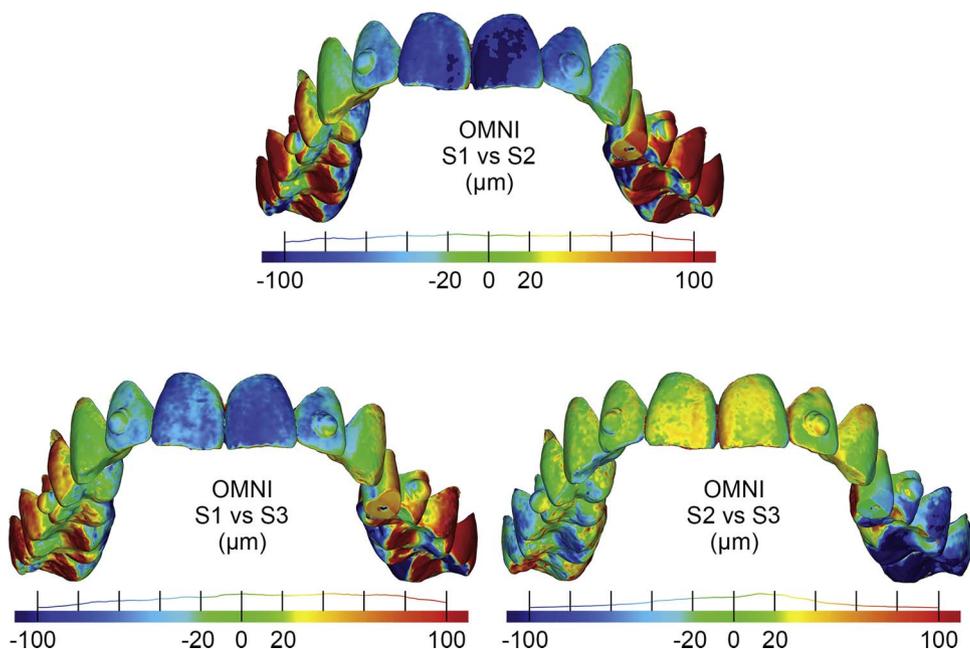


Fig. 9. Precision of OMNI IOS with cross-comparison for one subject. Color histogram depicting deviations with settings at nominal $\pm 20 \mu\text{m}$ and critical $\pm 100 \mu\text{m}$.

intraoral scanning is the cause for greater variations: operator bias, scanning protocol or a combination of subject anatomy, actual measurement sensitivity and software algorithms.

The difficulty of evaluations in vivo lies in accurately measuring as well as validating a reference-measurement that represents the truth. Although tactile or optical scanners, such as ATOS, can provide accuracy in standardized validations (ISO and VDI/VDIE respectively), showing accuracy down to a few micrometers, it is currently clinically and practically impossible to record an absolute truth. Any reference-measurement in vivo as presented in this study, or using transfer-guides [21], will include certain inaccuracies. However, if the accuracy of the ATOS system is maintained and in line with results of the precision, it will most likely exceed, with a clinically relevant margin, that of the tested IOS.

The findings in this study are based on 3D Compare Analysis, which is one of several methods used in metrology for assessing accuracy and precision. An alternative method with measurements between reference-bodies, as suggested by Kuhr et al. [21], was not performed in this dataset as it was considered challenging to reproduce and could include measurement bias. As the scans from IOS and conventional impressions will include inaccuracies, predominantly seen in interproximal areas and relating to the occlusal anatomy, only reference-bodies were used in selective best-fit-alignments. One factor that may affect the non-coating scanners is the use of reference bodies in Alumina, as refraction index varies somewhat from enamel, (1.72 vs 1.63) [15].

A limitation in this study is the anatomical constraints, as scan-data could only be acquired buccally and not further posterior than the second premolar area for accuracy analysis. The latter is a clear benefit

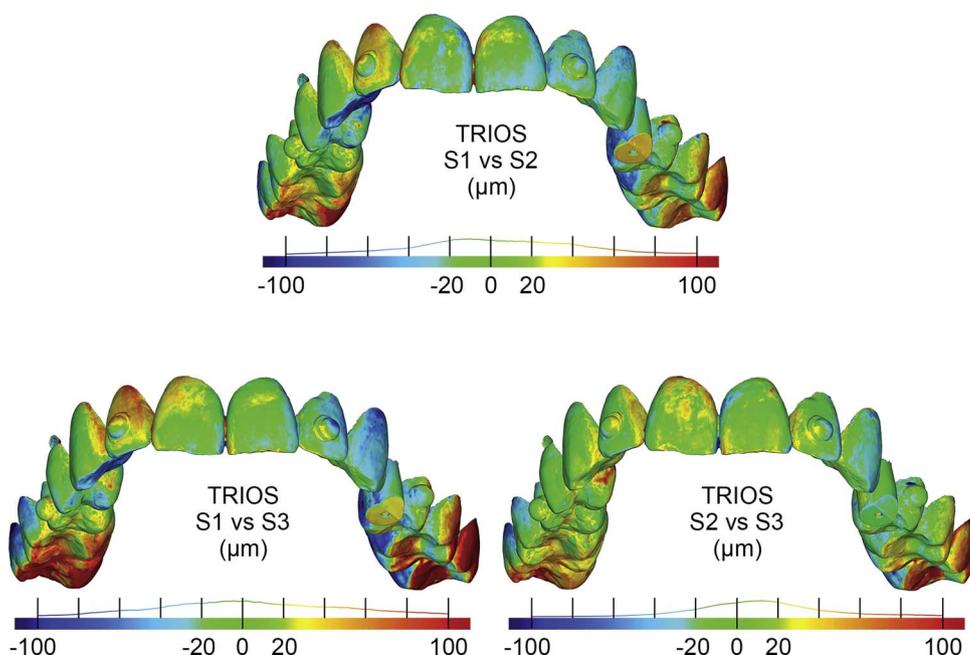


Fig. 10. Precision of TRIOS IOS with cross-comparison for one subject. Color histogram depicting deviations with settings at nominal $\pm 20 \mu\text{m}$ and critical $\pm 100 \mu\text{m}$.

of the transfer method described in a previous study [21]. However, the transfer method requires subjects to have a dentate situation suitable for a transfer guide to be used and due to the practical challenges, offers no evaluation of the precision of the transfer method in situ.

Within the limitations of this study, the method of validating intraoral scanners may be valuable for assessing accuracy of IOS and conventional impressions in vivo up to five units bilaterally from midline. It is not limited to the subject's dentate situation and could be used in other modalities, given the anatomical access. However, the method described in this study is time-consuming and requires extensive training, and may give rise to operator related errors.

Whilst there is a lack of consensus on critical deviation in different treatment outcomes, the deviations seen are within a range that can be considered clinically acceptable. Even though previous studies vary greatly in design and execution, as well as findings between systems, the numerical data is of a similar magnitude, both in vivo and in vitro [8,21].

The results in this study is valid for dentate arches with a single implant to be scanned. Evaluations of other treatment scenarios using IOS may however change the outcome due to IOS inaccuracies from edentulous areas with a higher level of non-attached tissues. Further studies are needed to fully understand those limitations of IOS, which raises the need for suitable in vivo evaluation methods.

5. Conclusion

It is vital that IOS has an equally or higher accuracy and precision than conventional impressions. The described methodology can be used for assessing accuracy of IOS and conventional impressions in vivo in up to five units bilaterally from midline. Accuracy varies between intraoral scanners and conventional impressions. 3M and TRIOS had a higher accuracy than OMNI. IMPR overlapped both groups. However, the deviations are within a similar magnitude for arches up to ten units.

Intraoral scanners can be used as a replacement for conventional impressions when restoring up to ten units without extended edentulous spans.

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References

- [1] M. Andersson, B. Bergman, C. Bessing, G. Ericson, P. Lundquist, H. Nilson, Clinical results with titanium crowns fabricated with machine duplication and spark erosion, *Acta Odontol. Scand.* 47 (5) (1989) 279–286.

- [2] M.M. Russell, M. Andersson, K. Dahlmo, M.E. Razzoog, B.R. Lang, A new computer-assisted method for fabrication of crowns and fixed partial dentures, *Quintessence Int.* 26 (11) (1995) 757–763.
- [3] M. Andersson, M.E. Razzoog, A. Oden, E.A. Hegenbarth, B.R. Lang, Procera: a new way to achieve an all-ceramic crown, *Quintessence Int.* 29 (5) (1998) 285–296.
- [4] J. Katsoulis, R. Mericske-Stern, L. Rotkina, C. Zbaren, N. Enkling, M.B. Blatz, Precision of fit of implant-supported screw-retained 10-unit computer-aided-designed and computer-aided-manufactured frameworks made from zirconium dioxide and titanium: an in vitro study, *Clin. Oral Implants Res.* 25 (2) (2014) 165–174.
- [5] A.S. Persson, A. Oden, M. Andersson, G. Sandborgh-Englund, Digitization of simulated clinical dental impressions: virtual three-dimensional analysis of exactness, *Dent. Mater.* 25 (7) (2009) 929–936.
- [6] W.H. Mormann, The evolution of the CEREC system, *J. Am. Dent. Assoc.* 137 (Suppl) (2006) 7S–13S.
- [7] D.J. Fasbinder, The CEREC system: 25 years of chairside CAD/CAM dentistry, *J. Am. Dent. Assoc.* 141 (Suppl 2) (2010) 3S–4S.
- [8] W. Renne, M. Ludlow, J. Fryml, Z. Schurch, A. Mennito, R. Kessler, A. Lauer, Evaluation of the accuracy of 7 digital scanners: an in vitro analysis based on 3-dimensional comparisons, *J. Prosthet. Dent.* (2016).
- [9] S.B. Patzelt, A. Emmanouilidi, S. Stampf, J.R. Strub, W. Att, Accuracy of full-arch scans using intraoral scanners, *Clin. Oral Investig.* 18 (6) (2014) 1687–1694.
- [10] A. Ender, A. Mehl, Full arch scans: conventional versus digital impressions?an in-vitro study, *Int. J. Comput. Dent.* 14 (1) (2011) 11–21.
- [11] A. Ender, A. Mehl, In-vitro evaluation of the accuracy of conventional and digital methods of obtaining full-arch dental impressions, *Quintessence Int.* 46 (1) (2015) 9–17.
- [12] A. Ender, A. Mehl, Accuracy of complete-arch dental impressions: a new method of measuring trueness and precision, *J. Prosthet. Dent.* 109 (2) (2013) 121–128.
- [13] A. Ender, T. Attin, A. Mehl, In vivo precision of conventional and digital methods of obtaining complete-arch dental impressions, *J. Prosthet. Dent.* 115 (3) (2016) 313–320.
- [14] A. Ender, M. Zimmermann, T. Attin, A. Mehl, In vivo precision of conventional and digital methods for obtaining quadrant dental impressions, *Clin. Oral Investig.* 20 (7) (2016) 1495–1504.
- [15] R.G. Nedelcu, A.S. Persson, Scanning accuracy and precision in 4 intraoral scanners: an in vitro comparison based on 3-dimensional analysis, *J. Prosthet. Dent.* 112 (6) (2014) 1461–1471.
- [16] P. Muller, A. Ender, T. Joda, J. Katsoulis, Impact of digital intraoral scan strategies on the impression accuracy using the TRIOS Pod scanner, *Quintessence Int.* 47 (4) (2016) 343–349.
- [17] B. Gimenez, M. Ozcan, F. Martinez-Rus, G. Pradies, Accuracy of a digital impression system based on parallel confocal laser technology for implants with consideration of operator experience and implant angulation and depth, *Int. J. Oral Maxillofac. Implants* 29 (4) (2014) 853–862.
- [18] H. Li, P. Lyu, Y. Wang, Y. Sun, Influence of object translucency on the scanning accuracy of a powder-free intraoral scanner: a laboratory study, *J. Prosthet. Dent.* (2016).
- [19] P. Seelbach, C. Brueckel, B. Wostmann, Accuracy of digital and conventional impression techniques and workflow, *Clin. Oral Investig.* 17 (7) (2013) 1759–1764.
- [20] F. Xiong, Y. Chao, Z. Zhu, Translucency of newly extracted maxillary central incisors at nine locations, *J. Prosthet. Dent.* 100 (1) (2008) 11–17.
- [21] F. Kuhr, A. Schmidt, P. Rehmann, B. Wostmann, A new method for assessing the accuracy of full arch impressions in patients, *J. Dent.* 55 (2016) 68–74.
- [22] R.C. Team, R. A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2016.
- [23] B.D.J. Pinheiro, S. DebRoy, D. Sarkar, R. Core Team, Nlme: Linear and Nonlinear Mixed Effects Models, (2017).
- [24] P.H.-P.S. Graves, L. Selzer, MultcompView: Visualizations of Paired Comparisons, (2015).