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CLINICAL RESEARCH

Complete arch accuracy of six intraoral scanning devices: A clinical study

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ABSTRACT

Statement of problem. Intraoral scanning systems have been replacing conventional workflows in dentistry as the primary method of documentation, diagnosis, and treatment. Despite their growing adoption, the accuracy of complete arch scans remains a critical challenge.

Purpose. The aim of this clinical study was to evaluate and compare the precision and trueness of 6 current intraoral scanners (IOS) for complete arch recording using a conventional high-precision impression technique as the control group.

Material and methods. In 10 participants, 3 complete arch scans of the maxillary and mandibular jaws were obtained using 6 IOSs - Emerald S (EME); MEDIT i900 (MED); Primescan (PRI); Primescan 2 (PS2); Aoralscan 3 (SHI); TRIOS 5 (TRI) - and 1 conventional impression (CONV) technique. CONVs were poured and digitized using a laboratory scanner. Precision was assessed from intragroup pairwise comparison, while trueness values were calculated by comparing IOS scan data with the corresponding conventional impressions using (90_10)/2-percentile values. Statistical analyses were performed using Welch ANOVA followed by Games–Howell post hoc tests and a linear mixed-effects model (P=.05).

Results. Precision values ranged from 21 ±4 µm for CONV up to 82 ±38 µm for group EME. CONV showed significantly higher precision compared with all IOSs (P>.05). No significant difference was found among PRI, PS2, MED or between SHI and TRI (P>.05). Trueness values ranged from 41 ±10 µm (PRI) up to 96 ±29 µm (EME). A significant effect of scanner group on trueness was found (P<.001), but no significant differences were detected between MED and PS2, between PRI and PS2, or between SHI and TRI (P>.05).

Conclusions. For dentate complete arch recordings, the standard remains conventional high-precision material. Among IOSs, significant differences concerning accuracy were found for complete arch scans, but they did not exceed 100 µm. (J Prosthet Dent 2026;136:136-143)

Intraoral scanners (IOSs) are being increasingly used in clinical dentistry as a digital alternative to conventional impressions, offering benefits such as improved patient comfort, workflow efficiency, real-time visualization, and enhanced clinician–patient communication.[1,2] Digital data can be directly applied for diagnosis, treatment planning, and restoration fabrication, eliminating physical replicas and enabling metric-based documentation and monitoring for novel clinical applications.[3–5] Despite these advantages, IOS accuracy - particularly for complete arch recordings - remains debatable. While high accuracy has been well documented for single-tooth and short-span scans,[6–9] complete arch reliability is less consistent,[9,10] largely because of error accumulation during image stitching, limited scanner field of view, and intraoral factors such as saliva, soft tissue motion, restoration materials, and patient movement.[11–15] These errors often originate in the anterior jaw segment and propagate to posterior regions.[6,16]

Most accuracy studies have been in vitro, assessing trueness and precision under controlled conditions[17,18]

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Clinical Implications

Intraoral scanning systems offer an effective means of replicating complete arch clinical situations, enabling the creation of digital casts suitable for a wide range of applications with clinically acceptable accuracy. However, when selecting an intraoral scanner, users should carefully evaluate the system's accuracy and its capabilities for data processing and integration to ensure alignment with their specific clinical and technical requirements.

which do not replicate clinical complexity. In vivo studies are essential but remain scarce and lack standardized protocols.[19] The International Organization for Standardization (ISO) 12836:2015 standard addresses laboratory scanners but not the challenges of complete arch intraoral scanning.[12]

Conventional impressions and gypsum casts remain the clinical benchmark. Although in vitro findings have reported conflicting outcomes, several studies have shown that high-precision materials such as silicone, polyether, polyvinyl siloxane (PVS), and vinyl siloxanether (VSE), combined with techniques like correction or double-mix method, can serve as an appropriate standard for comparing IOS accuracy.[6,20–24] A recent systematic review concluded that in vivo comparisons between digital scans and conventional impressions were insufficient for definitive conclusions.[19] Recent in vivo studies have evaluated IOS accuracy using parameters such as trueness and precision. Kwon et al[25] assessed both metrics across different scanners, while Iturrate et al[9] compared a single scanner against a newly developed reference gauge. Orejas-Perez et al[26] focused on the precision of 2 optical scanners, and Pellitteri et al[27] examined the trueness of three IOSs in comparison with a conventional PVS impression. Schlenz et al[28] conducted an in vivo study comparing four IOSs and a conventional impression technique for complete arch mandibular recording, evaluating trueness. The authors are unaware of an in vivo study with current scanning devices investigating the accuracy of complete arch scans and comparing them with conventional high-precision impression materials.

Therefore, the aim of the present in vivo study was to compare both the trueness and precision of several contemporary intraoral scanners for complete arch scans and additionally using a conventional impression technique as the reference standard. The null hypotheses were that no statistically significant differences with respect to both trueness and precision would be found between the different digital scanning systems and that no statistically significant differences in precision would be found between them and the conventional impression technique.

MATERIAL AND METHODS

This clinical study was approved by the Swiss Association of Research Ethics Committees (Ref. no. 2024–00618) and registered in the Swiss National Clinical Trials Portal and on ClinicalTrials.gov (NCT06658366) before the first participant was enrolled. Ten participants (n=10) were recruited from the patient file and the staff pool of the Center for Dental Medicine at the University of Zurich, where the entire study was conducted. The inclusion criteria were all sexes, 18 or more years, good general and dental health (spaces with a maximum of 1 missing tooth were permitted), and written informed consent. The exclusion criteria were under 18 years, addicts or with impaired cognitive abilities, periodontitis (pathological tooth mobility could falsify the study results), maximal mouth opening <3.5 cm, and those with extensive prostheses and/or a shortened arch from at least the second premolar. The number of conventional impressions and digital scans was calculated based on a recent in vitro study.[29] The a priori analysis for trueness resulted in an effect size of 21.2 with α=.05 and a power (1-β) of 0.95. Total sample size was N=14. For precision, the effect size was 14.3 with α=.05 and a power (1-β) of 0.95. Total sample size was also N=14.

Three conventional impressions of the maxillary and mandibular jaws were made for each participant, at the beginning, in the middle, and at the end of each session, using disposable impression trays (PRESIDENT Disposable Impression Trays; Coltène). Impression trays were treated with a universal adhesive (IDENTIUM Adhesive; Kettenbach) and filled with vinylsiloxane ether (VSE) impression material (IDENTIUM heavy and light; Kettenbach) using the simultaneous double-mix technique.[30] The oral dwell time was maintained at 4:30 minutes. Conventional impressions were immersed in a disinfectant bath for 5 minutes (MD 520 Abdruck-Desinfektion; DÜRR DENTAL), rinsed with water, and stored for at least 8 hours at room temperature and humidity. The impressions were poured by a dental laboratory technician with a Type IV dental gypsum (GC FUJIROCK EP Premium; GC Europe). After 48 hours of setting time the gypsum casts were scanned using a laboratory scanner (inEos X5; Dentsply Sirona) to generate standard tessellation language (STL) files (CONV). This laboratory scanner has been reported to have an accuracy of 2.1 ±2.8 µm for the reference object "Bridge," as assessed by the ISO 12836 standard,[31] and local on-site calibration showed a mean deviation of 3.7 µm for a reference circle (inLab CAD SW 16; Dentsply Sirona).

Six IOSs were used in this clinical study. For every IOS, 3 scans of maxillary and mandibular jaw were performed in every participant, including a habitual occlusion scan. Two experienced examiners (A.E. and J.B.) performed the scans in a rotating order. The IOSs used were EME (Emerald S; Planmeca), MED (MEDIT i900; MEDIT), PRI (Primescan; Dentsply Sirona), PS2 (Primescan 2; Dentsply Sirona), SHI (Aoralscan 3; SHINING 3D Dental), and TRI (TRIOS 5 wireless; 3Shape A/S). During data acquisition the lips and cheeks were retracted (OptraGate; Ivoclar AG). All scanning devices were used in accordance with the manufacturer's recommendations, including calibration and scanning strategy, except for group PRI, for which its own clinically tested scanning strategy was used (Table 1). All scans were exported as STL files in the highest possible resolution.

For further data processing, the exported STL files from the scans and the conventional impressions were imported into a 3-dimensional (3D) analysis software program (GOM Inspect 2018; GOM GmbH). For trueness, each STL data file was compared with the respective data set of the conventional impressions. The pairwise comparison of all STL files within 1 group gave the basis for the precision. The evaluation process followed the ISO 5725–1 criteria and was described in Ender et al[6] and specified in more detail in Mehl et al.[32] The process was as follows: after superimposition of the mesh surfaces according to the best-fit alignment, the distances were measured point-to-surface using the signed nearest neighbor method and sorted into a histogram. From that, the measure for deviation of each pairwise surface superimposition was defined as the (90_10)/2-percentile value.[6,32] As a result, for each group, 3 precision and 3 trueness values were derived, which corresponded to a total of 420 precision and 360 trueness values (3×2 jaws (maxillary or mandibular) × 10 participants × 6 scan devices or × 7 including the conventional impressions).

The statistical analysis was performed with a software program (IBM SPSS Statistics, v30.0.0.0; IBM Corp.). First, a descriptive analysis was done to extract the mean, standard deviation (SD), median, and 75% minus 25% percentile (IQR) values. To investigate

Table 1. Recording and postprocessing techniques used to generate standard tessellation language (STL) files

Test group	System	Software program	Recording technique	Postprocessing
CONV	IDENTIUM heavy and light		Disposable impression trays (PRESIDENT Tray; Coltène)) Adhesive IDENTIUM Adhesive; Kettenbach Setting time: 4.5 min Storage time prior to pouring: 8 h Storage time prior to digitizing: 24 h	Poured with gypsum type IV, digitized with inEOS X5 (inlab CAD SW 22.1), export to STL file
EME	Emerald S	Romexis v.6.4.7.129	As recommended by manufacturer https://www.planmeca.com/globalassets/planmeca/1-planmeca-usa-modernization/cadcam/dental-scanning/emerald-s/manuals/6.4-emerald-s-user-manual.pdf// (User manual)	Direct export to STL file
MED	MEDIT i900	Medit Link v.3.0.4	As recommended by manufacturer https://www.medit.com/de/a-proper-scan-strategy-for-scanning-a-full-arch/(User manual)	Direct export to STL file
PRI	Primescan	Cerec Software v.5.2.9	Optimized scanning strategy: Scan starts at the oral surface of the canine, up to the contralateral distal tooth rotating the camera to the occlusal aspect and scanning the occlusal/incisal surface back to the starting point. The scanner is repositioned at the distal occlusal surface and rotated to the buccal aspect, scanning the buccal surface towards the starting point of the canine tooth. The final scanning path starts disto-occlusally, turns orally. The camera is guided in a 90-degree angle to the tooth-surfaces towards the incisors. Same procedure is repeated for the contralateral half of the dental arch to complete the complete arch scan.	Direct export to STL file
PS2	Primescan 2	Firmware v.1.4.1,October 2024	As recommended by manufacturer https://www.dentsplysirona.com/en-no/support/resources/download-center/download-details.html?assetPath=/content/dam/master/product-procedure-brand-categories/digital-impression/product-categories/intraoral-scanners/ifu/DIM-IFU-Primescan-2-EN-6816685-2025-11-14.pdf (User manual)	Direct export to STL file
SHI	Aoralscan 3	IntraoralScan v.3.4.1.3	As recommended by manufacturer https://www.shining3d.top/download/TlajufeE062hp0oZ6CpOVg%3D%3D%3AZ36TB1zJSmzFb34uKqA2W36%2FL5QdtstmlHkHQqTQnu42eLi3N7qGSfP0fjZxxW6KDtM0Nx9XqImn9a5A8CjeTA%3D%3D (User manual)	Direct export to STL file
TRI	TRIOS 5	TRIOS Software v.24.3.1	As recommended by manufacturer https://3shape.widen.net/view/pdf/bitoot5rkw/TRIOS-Module-User-Manuals—R1.0-B-DE.pdf?t.download=true&u=0vknty(User manual)	Direct export to STL file

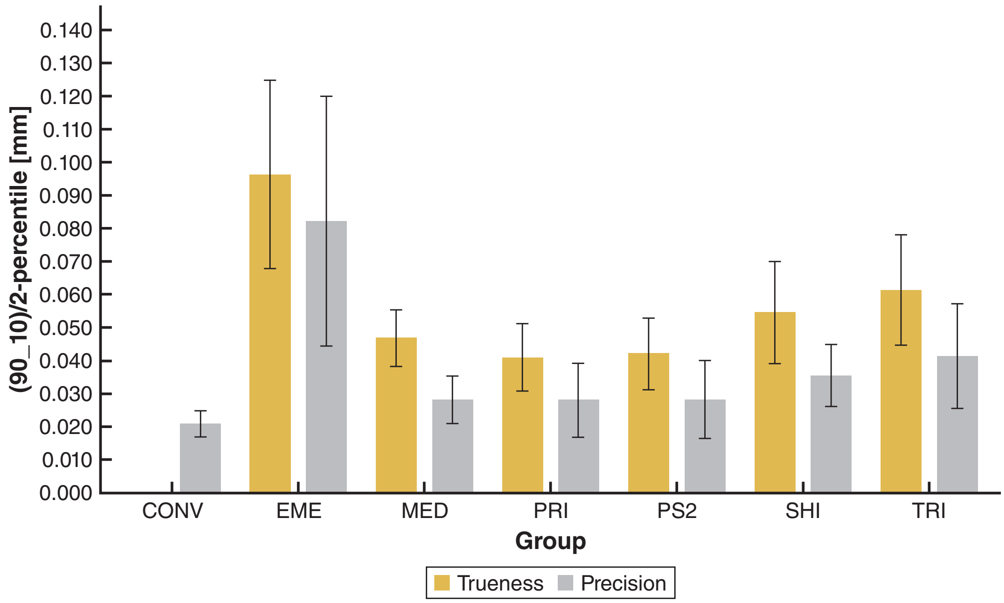

Figure 1. Bar diagrams showing precision for conventional impression method, as well as trueness and precision values for digital scans using (90_10)/2-percentile values. Bars represent mean value; error bars represent standard deviation.

differences in precision (7 groups, n = 60 each; N = 420) and trueness (6 groups, n = 60 each; N = 360) separately, 1-way ANOVA using the Welch test was conducted. Assumptions were checked prior to analysis: normality using the Shapiro–Wilk test, Q–Q plots, and homogeneity of variances using the Levene test (P<.001 for both outcomes). Given the sample size and the robustness of Welch ANOVA to mild nonnormality, parametric inference was considered appropriate. Because of variance heterogeneity, post hoc comparisons used the Games–Howell tests. To determine that the conventional impression can be a reference method, the 2 intraoral devices with the highest precision were selected. The precision of these intraoral scanning groups was then compared with the conventional impression across all participants to account for participant variability. For that, a linear mixed effects model was used with the scanning/impression group as the fixed effect and the participant as the random effect (α=.05).

RESULTS

Ten participants were included in the study with a mean ±SD age of 32.9 ±7.9 years. None of the recruited participants had to be excluded. The post hoc power analysis for achieved power with a total sample size of 60 (n=10 per group) resulted in an effect size for trueness at 17.7 at α=.05 and a power (1-β) of 1.0. Achieved power with a total sample size of 70 for precision resulted in an effect size of 17.8 with α=.05 and an achieved power (1-β) of 1.0.

Table 2. Results for trueness and precision values for digital and conventional recordings using (90_10)/2-percentile evaluation parameter. Values given as median [interquartile range (IQR)] and mean ±standard deviation (SD); all values in µm

	Median [IQR] and Mean ±SD of (90_10)/2-percentile			
Group	Trueness		Precision	
CONV	-	-	21 [6]	21 ±4
EME	91 [31]	96 ±29	78 [58]	82 ±38
MED	46 [11]	47 ±9	27 [9]	28 ±7
PRI	39 [12]	41 ±10	29 [15]	28 ±11
PS2	40 [17]	42 ±11	26 [17]	28 ±12
SHI	53 [17]	55 ±15	34 [14]	35 ±10
TRI	59 [21]	61 ±17	38 [17]	41 ±16

The results of the trueness and the precision of the different scanning devices and the precision of the conventional workflow in the case of complete arch impressions are shown in Figure 1 and Table 2. The precision ranged from 21 ±4 µm for the conventional impression and 28 ±11 µm for the scanning group PRI up to 82 ±38 µm for the group EME. The 1-way ANOVA using the Welch test revealed a significant effect of impression group on precision (P<.001; with F(6176.1) =58.8). The results of the pairwise post hoc comparisons using the Games-Howell test can be seen in Table 3. No significant difference was found among PRI, PS2, MED and between SHI and TRI (P>.05). Notably, the conventional impression workflow showed significantly higher precision compared with all digital scan groups (P<.05). Figure 2 shows the precision of the conventional impression compared with both scanners with the highest precision (PRI and MED), plotted separately for each participant. It shows that for all participants (except

Table 3. Cross-tables for precision and trueness showing statistical pairwise differences after 1-way ANOVA with post hoc Games-Howell test across all test groups. X indicates statistically significant differences ($P<.05$).

Precision	CONV	EME	MED	PRI	PS2	SHI	TRI
CONV		X	X	X	X	X	X
EME	X		X	X	X	X	X
MED	X	X				X	X
PRI	X	X				X	X
PS2	X	X				X	X
SHI	X	X	X	X	X		
TRI	X	X	X	X	X		

Trueness	EME	MED	PRI	PS2	SHI	TRI
EME		X	X	X	X	X
MED	X		X		X	X
PRI	X	X			X	X
PS2	X				X	X
SHI	X	X	X	X		
TRI	X	X	X	X		

1 with equal precision), the precision of the group CONV was higher than the precision for the scanning devices and that the values for all participants were consistent within a narrow range from approximately 18 to 23 µm. The statistical analysis applying the linear mixed effects model revealed a significant effect of impression group on precision ($P<.001$; with $F(3,21.4)=299.4$). Further, the model estimated the residual variance to be 6.1×10^{-5} mm^2 (corresponds to SD of 8 µm; $SE=6.6\times10^{-6}$) and the participant variance to be 4.2×10^{-6} mm^2 (corresponds to SD of 2 µm; $SE=3.6\times10^{-6}$). These values indicated that the model fit the data well, with minimal unexplained variability and low variability between participants. Pairwise comparisons indicated that group CONV had significantly higher precision compared with MED and PRI ($P<.001$ for both comparisons), a strong indicator that conventional impressions can still be regarded as the reference standard in the case of complete arch recording. The trueness ranged from 41 ±10 µm for the scanner group PRI up to 96 ±29 µm for the group EME. The 1-way ANOVA using the Welch test revealed a significant effect of scanner group on trueness ($P<.001$; with $F(5162.6)=53.1$). The results of the pairwise post hoc

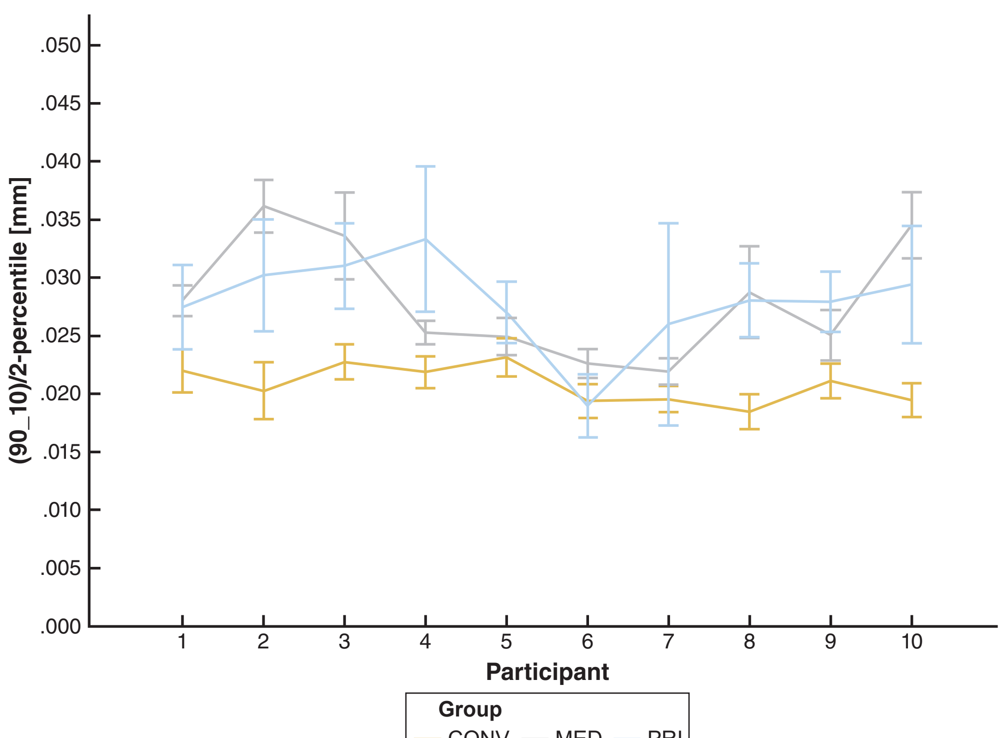

Figure 2. Line diagrams showing precision (mean ±standard deviation of (90_10)/2-percentile values) for groups CONV, MED, and PRI presented for each participant. Line represents mean value; error bars represent standard deviation.

comparisons using the Games-Howell test (Table 3) showed no significant differences between MED and PS2, between PRI and PS2, and between SHI and TRI (P>.05).

DISCUSSION

The present study investigated the trueness and precision of several contemporary intraoral scanners for complete arch recordings in clinical situations. Additionally, they were compared with the conventional impression workflow. The null hypotheses that no statistically significant differences with respect both to trueness and precision would be found between the different digital scanning systems and that no statistically significant differences in precision would be found between them and the conventional impression technique were rejected.

The focus of this study was placed on capturing digital scans of complete or nearly complete dentitions because such recordings represent a common clinical scenario, where digital scans are considered for single-unit or fixed partial denture restorations, as well as for diagnostic, documentation, or monitoring purposes. Consequently, the use of IOSs in recordings involving extensive edentulous areas or fully edentulous jaws was beyond the scope of this investigation. Similarly, situations requiring the scanning of dental implants or scan bodies were excluded. With this focus in mind, the present study evaluated currently available IOSs for their suitability in complete arch recordings. Conventional high-precision impressions served as the control group.

A recent meta-analysis by Kong et al,[19] which applied PRISMA criteria, concluded that because of the limited number of in vivo studies (only 2 meeting inclusion criteria), no definitive conclusions could be drawn regarding whether digital scanning devices were comparable with or better than conventional impressions using high-precision materials. Pellitteri et al[27] compared IOSs with conventional PVS impressions and reported deviations of approximately 100 to 200 µm. Schlenz et al[28] found no significant differences between the tested IOSs compared with the conventional polyether impression but with this polyether impression still showing the lowest deviations, especially with respect to long-span distances.

The present findings indicated that, even with recently introduced IOSs, CONVs using VSE material exhibit significantly higher precision under in vivo conditions. When accounting for participant-specific variables using a linear fixed effects model, CONVs continued to show statistically better precision compared with the 2 most accurate IOSs. Notably, the precision values across all groups fell within a narrow bandwidth (Fig. 2), suggesting that individual participant factors - while potentially influencing accuracy - did not compromise the overall quality of the conventional impressions.

Trueness was defined as the "closeness of agreement between the average value obtained from a large set of test results and an accepted reference value."[33] However, according to ISO standards (such as, VIM item 2.11[34]), the true value of a measurement is inherently unknown.[33,34] Therefore, ISO guidelines recommend reporting the precision of the reference measurements via a standard error, which should be significantly smaller than the expected accuracy of the systems being evaluated (for example, the ISO 5725–1 standard suggests a factor of around 0.2).

In the present study, CONVs were used as the reference. A short calculation based on Figure 1 and Table 2 shows that the standard error of CONV was approximately 12 µm. Figure 2 confirms that this value remains consistent across participants. Compared with the trueness values of the IOSs, this standard error was approximately 3 to 7 times smaller - even for the best-performing IOSs - mostly fulfilling the ISO requirement for a valid reference.

In general, high precision does not necessarily imply high trueness, as systematic biases may still be present and can compromise overall accuracy.[6,32,33] To address this, an in vitro study was conducted prior to the in vivo investigation to evaluate both the precision and trueness of conventional VSE impressions using complete dentition casts.[29] The results showed an in vitro trueness of around 24 µm, which was within the same range as the precision observed in vivo. This consistency suggested that the conventional VSE impression technique does not exhibit a relevant significant bias (<4 µm), such as calibration errors or systematic deformations. As a result, it could be inferred that the in vivo trueness of the CONVs approximates their precision, supporting the reliability of this method as a reference standard. This rationale underpinned the decision to use the conventional impression workflow as the benchmark in this study. The digital scans were compared against this standard to determine the trueness of the intraoral scanning devices. However, given the minor additional errors of the conventional impression, in the worst case, the trueness of the most precise scanning devices may even be lower (more accurate). Therefore, the trueness values of the IOSs can be seen somehow as an upper limit.

The comparison of IOSs revealed significant differences in both trueness and precision. Notably, the ranking of the IOSs remained largely consistent across both metrics, with trueness values consistently slightly higher than precision values for all devices. This discrepancy suggests the presence of systematic errors, such as calibration inaccuracies or stitching artifacts, that continue to influence overall accuracy.

An observation from the scanner comparison was the emergence of 3 distinct accuracy tiers. The highest-performing cohort included PRI, PS2, and MED; a second tier with slightly lower accuracy comprised SHI and TRI. The lowest-performing group was represented by EME.

Scanners using parallel optical measurement methods (such as confocal imaging) have been reported to offer advantages over those based on triangulation principles (such as structured light, stereovision, or photogrammetry).[35] However, the results of this study indicate that representatives of both optical principles are present within each accuracy tier. This finding suggests that, at the current level of development, the underlying scanning technology alone does not reliably predict the performance of intraoral scanners.

In contrast, a recent in vitro study by Baresel and Baresel[36] reported that scanner acquisition technology influenced complete arch digital scan accuracy. Their investigation included a device using a novel multidirect capture (MDC) technology, which demonstrated lower linear relative errors in both trueness and precision compared with confocal and structured-light systems. However, no MDC-based system was included in the present in vivo study.

In addition to its focus on fully dentate participants this study has further limitations. It did not include participants with extensive restorations or material surfaces such as metal alloys or ceramics, nor did it account for clinical scenarios involving prepared teeth. These conditions may present different optical and morphological challenges that could have influenced the performance of IOSs. Future research should aim to investigate a more diverse range of patient scenarios, including those with dental implants, partially edentulous arches and complex restorative cases. It would also be valuable to compare the best-performing IOSs identified in this study with emerging technologies such as MDC-based systems to evaluate potential improvements in accuracy and clinical applicability.

CONCLUSIONS

Based on the findings of this in vivo study, the following conclusions were drawn::

1. CONVs using high-precision VSE material demonstrated the highest precision, significantly outperforming all tested IOSs. As such, the conventional workflow remains the standard for complete arch recordings of fully dentate arches.
2. IOSs could be categorized into 3 accuracy tiers based on trueness and precision. The highest accuracy was achieved with Primescan, Primescan 2, and MEDIT i900, followed by Aoralscan 3 and TRIOS 5, and the lowest accuracy was achieved with Emerald S.
3. The optical measurement principle (confocal imaging versus triangulation principles) did not correlate with the accuracy of the IOSs in this study, indicating that current device performance is not solely determined by the underlying scanning technology.

PATIENT CONSENT

The authors confirm that written informed consent has been obtained from the involved participants.

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CRediT authorship contribution statement

Andreas Ender: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Writing – Review and Editing. **Jenny Buhl**: Funding acquisition, Investigation, Project administration, Visualization, Writing – original draft**,** Writing – review and editing. **Albert Mehl**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Visualization, Writing – original draft**,** Writing – review and editing.

All authors gave their final approval and agree to be accountable for all aspects of the work.

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