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Full arch accuracy of intraoral scanners with different acquisition technologies: An in vitro study

Ingo Baresel [*], Jens Baresel

German Society for Digital Oral Impression (DGDOA), Germany

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ABSTRACT

Objectives: To evaluate the full arch trueness and precision of intraoral scanners (IOS) using different acquisition technologies.

Methods: Four 8 mm in diameter metal spheres were embedded into a dentate type IV dental stone cast model. Six distances among the centers of the spheres were measured with a coordinate measuring machine and used as references. The model was digitized thirty times with two confocal scanners (Trios 5 and CS3800), two structured light scanners (i700 and AS260) and one multi-direct capture (MDC) scanner (Lumina) by three trained operators ($n = 90$). Six distances in the scan files were measured and calculated for relative errors of trueness, precision and plane deviation (the perpendicular distance from each sphere's center to a reference plane representing a vertical error). Differences among scanners in terms of trueness and precision were analyzed with multivariable analysis, mixed-effect model and Tukey's multiple comparisons ($\alpha=0.05$; $p < 0.05$ indicating significance).

Results: Scanner type influenced full-arch accuracy, with the iTero Lumina exhibiting the lowest linear relative errors for trueness (0.04 % vs. 0.071 % for i700, 0.074 % for AS260, 0.089 % for CS3800, and 0.14 % for TRIOS5; $p < 0.0001$) and precision (0.032 % vs. 0.073 % for CS3800, 0.074 % for i700, 0.077 % for AS260, and 0.1 % for TRIOS5; $p < 0.01$). Plane deviation, the perpendicular distance from each sphere's center to a reference plane, ranged from 19 µm (Lumina) to 33–120 µm (others), with differences not statistically significant ($p > 0.05$).

Conclusion: This in vitro study indicated that intraoral scanner acquisition technology influences full-arch digital impression accuracy, with MDC technology demonstrating lower linear relative errors in trueness and precision compared to confocal and structured-light technologies. Further clinical research is needed to validate these findings.

Clinical Significance: As the first study to assess full-arch accuracy of an IOS with MDC technology, this study indicates that MDC may offer an accurate and reliable method for full-arch impressions.

1. Introduction

The trueness and precision of intraoral scanners (IOS) depend on the distance between scanned points. Studies consistently show that shorter spans, such as those covering individual teeth, achieve greater accuracy than full-arch scans [1,2]. A wider field of view (FOV) addresses this challenge by reducing the number of images needed to capture extended distances, thereby minimizing the stitching process and its subsequent misalignment errors—a common source of distortion in long-span scans [3–7].

Most IOS reconstruct 3D images using structured light or confocal imaging, established technologies that rely on a rear-mounted light source within the scanning wand [8,9]. Consequently, the maximum FOV is proportional to the cross-sectional area of the light beam projected from the wand's posterior to its anterior end. Traditionally, expanding this FOV demands a larger wand to accommodate a broader beam, often compromising ergonomics and intraoral maneuverability. In February 2024, Align Technology introduced the iTero Lumina scanner, featuring multi-direct capture (MDC) technology—a novel approach to intraoral imaging [10]. Equipped with six cameras arranged in three pairs and five structured light projectors, it emits blue and green diode lasers through a diffractive element to produce a hexagonal spot pattern. Each spot is captured by multiple cameras (typically two to four) from varying angles, ensuring precise triangulation of spatial coordinates. By embedding all optical components at the wand's tip, MDC eliminates the need for rear illumination, decoupling FOV from wand

* Corresponding author at: Obere Bahnhofstraße 22 90556 Cadolzburg, Germany.
E-mail address: ingo.baresel@t-online.de (I. Baresel).

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size measuring dimensions of 21 × 15 mm at 0 mm and 36 × 27 mm at 10 mm scanning distance [11].

Evaluating IOS full-arch accuracy presents significant challenges, stemming from variable clinical conditions and the inherent complexities of scanning procedures [12,13]. In vitro studies are favored over in vivo assessments because they offer controlled environments with stable reference points, reducing the impact of confounding factors like saliva, tongue movement, and dynamic soft tissues. This setting facilitates precise performance evaluations, yielding more reliable predictions of clinical accuracy [14]. In May 2015, the American Dental Association (ADA) and the American National Standards Institute (ANSI) introduced Standard No 132, "Scanning Accuracy of Dental Chairside and Laboratory CAD/CAM Systems," which details test methods for assessing the repeatability, reproducibility, and accuracy of dental 3D metrology devices, using a coordinate measuring machine (CMM) as the reference [15]. This in vitro study aimed to compare the full-arch accuracy of five IOS devices—two employing confocal imaging with rear illumination (Trios 5 and CS3800), two using structured light with rear illumination (i700 and AS260), and one with MDC technology (Lumina)—adhering strictly to the ANSI/ADA 132 standard for rigorous, reproducible evaluations.

The null hypothesis posited that MDC, with its broader FOV, would surpass rear-illumination scanners in long-span accuracy.

2. Materials and methods

In the present study a dentate, type IV dental stone cast model, incorporating four metal spheres 8 mm in diameter at the location of the first premolars and second molars was used (Fig. 1). The model underwent precision probing to acquire reference data for the distances between the spheres using a CMM (LK Evolution) with Camio software version 4.6. The model was then digitized using two confocal scanners (3Shape Trios 5, and Carestream CS3800), two structured light scanners (Medit i700 and Allied Star AS260) and one MDC scanner (iTero Lumina) Table 1.

Three trained operators with 8, 10, and 14 years of experience in intraoral scanning were selected. To minimize operator fatigue associated with the scanning process, a 5-minute rest period was implemented after every three scans. All scans were performed at room temperature in a controlled, windowless environment to eliminate interference from external light sources. The dental operatory light was turned off, and ambient illumination was provided solely by ceiling-mounted light-emitting diode (LED) fixtures, ensuring uniform lighting conditions. The manufacturer-recommended scan pattern was used for each scanner, with thirty scans performed per IOS per operator, totaling ninety scans per IOS across the three operators.

Table 1
Optical technology and field of view specifications.

	Manufacturer	Technology	Field of view [11,39,40-43]
iTero Lumina	Align Technologies, San Jose, CA, USA	Multi-direct capture	21×15 mm @0mm 36×27 mm @10mm
TRIOS 5	3Shape, Copenhagen, Denmark	Confocal imaging	15.9 × 15.3mm@ Near focus 19.5 × 18.8 mm @Far focus
CS3800	Carestream Dental, Atlanta, GA	Confocal imaging	16×14mm
i700	Medit, Seoul, South Korea	Structured light	15×13 mm (Standard tip)
AS260	Alliedstar, Shanghai, China	Structured light	16×14 mm (L) 12×12 mm (S)

All data were imported into a metrology-grade analysis software program (Geomagic Control X) in standard tessellation language (STL) format for evaluation. Linear relative error, total bias, and plane deviation of the spheres were calculated as follows:

Linear Deviation Total Bias (Trueness and Precision). Six linear distances between the centers of the spheres were measured and compared with reference CMM measurements. The relative error for trueness was determined by taking the absolute difference between the average distance obtained from all scans and the true distance from the CMM,

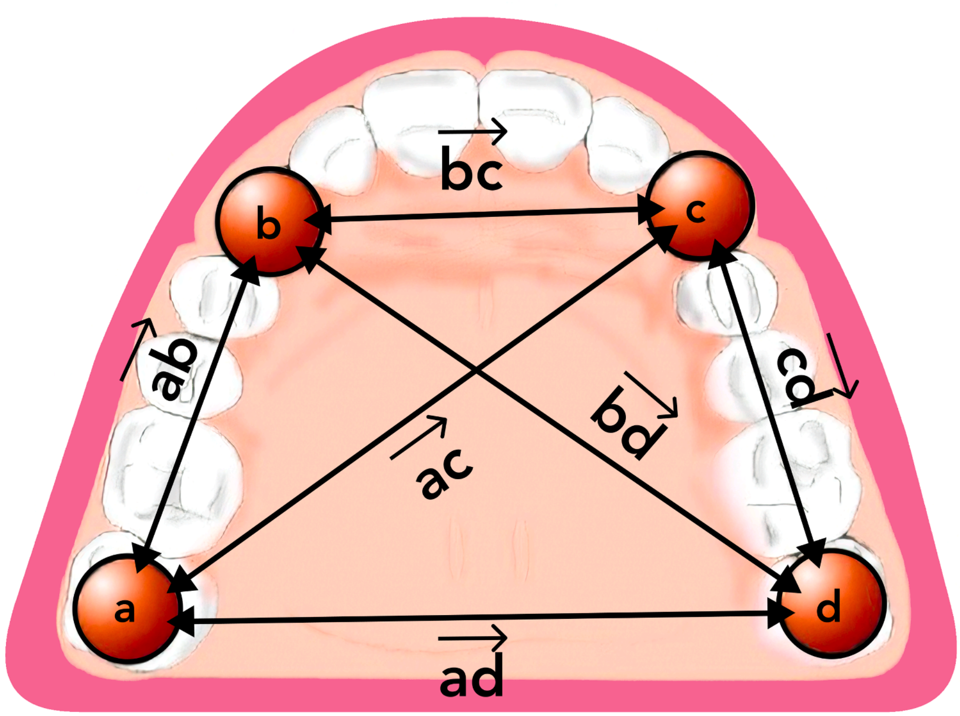

Fig. 1. Dentate cast model with four metal spheres.

dividing this by the true distance, and expressing it as a percentage. For precision, the standard deviation of the measured distances from all scans was calculated, then divided by the true value to obtain the relative standard deviation, also expressed as a percentage. Bias for each distance was determined as the difference between the average measured distance and the true distance, with total bias calculated as the sum of the absolute biases for each of the six measured distances. Total error was obtained by summing the relative errors for each distance.

Plane Deviation. For each sphere, a reference plane was defined by fitting a best-fit plane through the centers of three spheres, and the perpendicular distance from the fourth sphere to this plane was measured. This measured distance was compared with the corresponding distance obtained from the CMM measurements.

To assess linear deviation, we calculated the relative errors of trueness and precision for each scanner. Relative error was chosen to provide a proportional measure of accuracy across varying distances, aligning with clinical benchmarks and facilitating comparisons. Summary statistics included means, medians, standard deviations, and 95 % confidence intervals (95 % CIs). The calculated statistical measures for plane deviation included the mean, median, maximum, and minimum deviations as well as standard deviations and 95 % CIs. To compare the performance of the different scanners, one-way analysis of variance (ANOVA) test was conducted, followed by Tukey's honestly significant difference (HSD) post hoc tests for pairwise comparisons. To account for operator-specific variability, linear mixed-effects models were applied using the lme4 R package [16,17], with the scanner as a fixed effect and the operator as a random effect. This modeling approach allowed us to assess the effect sizes of the differences between the scanners while controlling for operator variability. All statistical analyses were performed using R software and statistical significance was set at $p < 0.05$.

3. Results

A comprehensive dataset including 2700 data points was gathered, which included three trained operators, five different scanning devices, thirty scans per device per operator, and six measured distances. These data points were then compared with ground truth measurements. The performance of each scanner was evaluated in terms of the trueness and precision across multiple datasets.

3.1. *Linear deviation total bias (trueness and precision)*

Fig.2 Shows the relative error for trueness, indicating the deviation from actual dimensions. Overall, the trueness of the tested scanners ranged from 0.0.04 % to 0.73 %, with a 95 % CI ranging from 0.037 % to 0.15 %. The linear mixed-effects model comparing the total bias across the six distances among all scanners, showed that the iTero Lumina provided a significantly lower total bias than all the other scanners ($p <$ 0.0001). Specifically, the total bias of all other scanners was approximately 0.0875–0.2965 mm greater than that of the iTero Lumina (Table 2). Multivariable analysis of linear deviation odds ratios (OR) for each intraoral scanner, compared to the Lumina, indicated that the Lumina scanner had a significantly lower probability of deviation (OR: 0.03–0.15, $p < 0.01$, Table 3).

The ratio of acceptable scans across all tested conditions was 99.6 %, 97.5 %, 95.9 %, 95.8 % and 88.1 %. for Lumina, AS260, CS3800, i700 and TRIOS5 respectively ($P = 0.0005$).

Table 2
Multivariable analysis comparison of scanner accuracy with Lumina as reference in the linear deviation analysis.

	Difference	SE	P-value
AS260	0.0875	0.0205	<0.0001
CS3800	0.1354	0.0202	<0.0001
i700	0.0928	0.0202	<0.0001
TRIOS5	0.2965	0.0203	<0.0001

Difference represents deviation in linear accuracy for each scanner relative to Lumina baseline, with higher values indicating greater deviation and reduced linear accuracy. Standard error (SE) represents reliability of the estimate, where lower SE values indicate more consistent and stable measurements. P-value determines statistical significance of deviation from Lumina, with values below 0.05 suggesting a statistically significant difference.

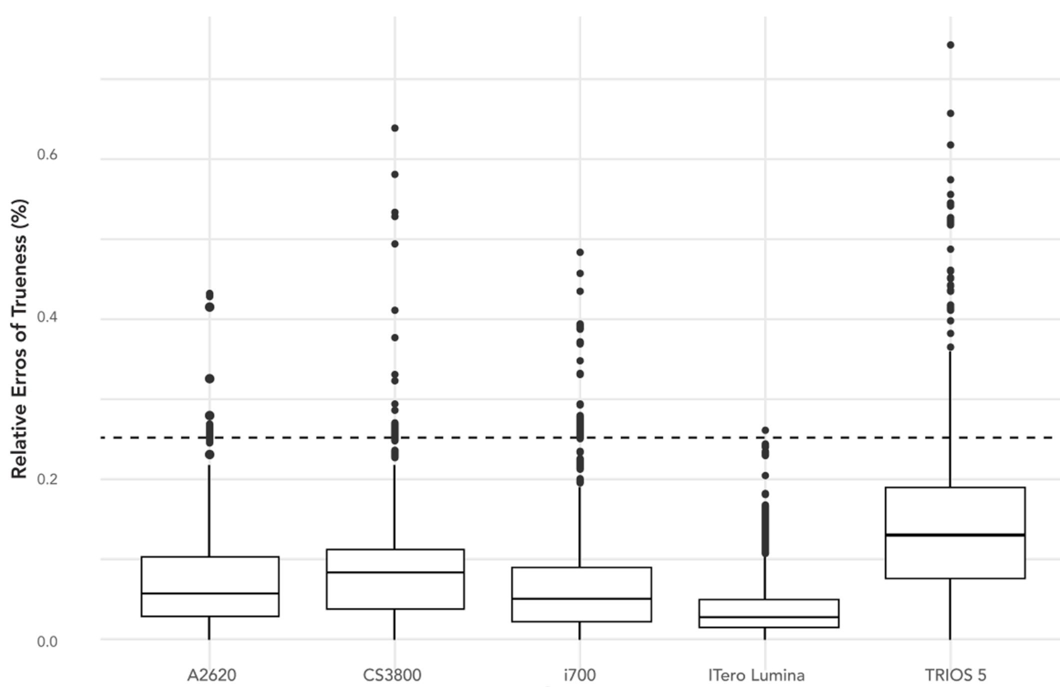

Fig. 2. Relative Error of Trueness of linear dimensions measured from intraoral scan data (relative error in percentage). Top of the box (upper hinge) represents the 75th percentile, and bottom of the box (lower hinge) represents the 25th percentile. Whiskers represent the maximum and minimum values. Circles represent outliers.

Table 3
Multivariable analysis of linear deviation odds ratios (OR) for each IOS compared to that of Lumina.

Variable	log (OR)	OR	95 % CI for OR	P-value
AS260	−1.92	0.15	(0.02, 0.54)	0.0119
CS3800	−2.4	0.09	(0.01, 0.31)	0.0012
i700	−2.52	0.08	(0.01, 0.27)	0.0006
TRIOS 5	−3.56	0.03	(0, 0.09)	<0.0001

The odds ratio (OR) quantifies the likelihood of deviation events for each scanner relative to Lumina, with values below 1 indicating fewer deviations and values above 1 indicating more. The log (OR) provides a transformed view of deviation impact, while the 95 % confidence interval (CI) for OR represents the range within which the true OR is expected to fall with 95 % certainty. The p-value indicates the statistical significance of the comparison to Lumina, with values below 0.05 suggesting a significant difference in deviation likelihood.

Fig.3 Shows precision error, reflecting measurement consistency. Precision values ranged from 0.015 % to 0.24 %, with a 95 % CI of 0.024 % to 0.12 %. The iTero Lumina demonstrated significantly superior precision compared to all other scanners, exhibiting lower precision bias ($p < 0.001$). Specifically, the precision bias of the other scanners was approximately 0.1922–0.4111 % higher than that of the iTero Lumina (Table 4).

3.2. Plane deviation

Fig. 4. Shows the plane deviation accuracy. Mean plane deviations of the tested scanners were 19 µm, 33 µm, 43 µm, 45 µm and 120 µm for Lumina, TRIOS5, i700, AS260 and CS3800 respectively. Tukey's multiple comparisons of mean plane deviations analysis show that all scanners in this study performed significantly better than the CS3800 ($P < 0.0001$). Differences in performance observed among the remaining four scanners were not statistically significant. (Table 5)

Table 4
Multivariable analysis comparison of scanner precision with Lumina as reference in the linear deviation analysis.

	Difference	SE	P-value
AS260	0.2699	0.0319	<0.0001
CS3800	0.2505	0.0319	<0.0001
i700	0.2553	0.0319	<0.0001
TRIOS5	0.4111	0.0319	<0.0001

Difference represents deviation in precision for each scanner relative to Lumina baseline, with higher values indicating greater deviation and reduced precision. Standard error (SE) represents reliability of the estimate, where lower SE values indicate more consistent and stable measurements. P-value determines statistical significance of deviation from Lumina, with values below 0.05 suggesting a statistically significant difference.

3.3. Inter-operator variability

Fig. 5. Shows the inter-operator variability. Overall, the iTero Lumina scanner showed consistent performance across all users, with relatively low standard deviations. The AS260 scanner exhibited greater variability in both mean values and standard deviations among users. The CS3800 scanner demonstrated high accuracy but also showed higher variability in precision among users. The i700 scanner displayed consistent performance across all users with low standard deviations. The TRIOS5 scanner showed higher variability in both accuracy and precision among users than the other scanners.

4. Discussion

In prosthodontics, obtaining precise impressions is fundamental, as accuracy directly influences prosthetic quality and longevity [18]. Recent advancements have introduced IOS, enabling the direct creation of virtual three-dimensional models and fully digital prosthetic workflows. The accuracy of IOS, a critical parameter for evaluation, varies by application. Literature indicates that for single-tooth restorations and fixed partial dentures up to four units, IOS accuracy matches that of

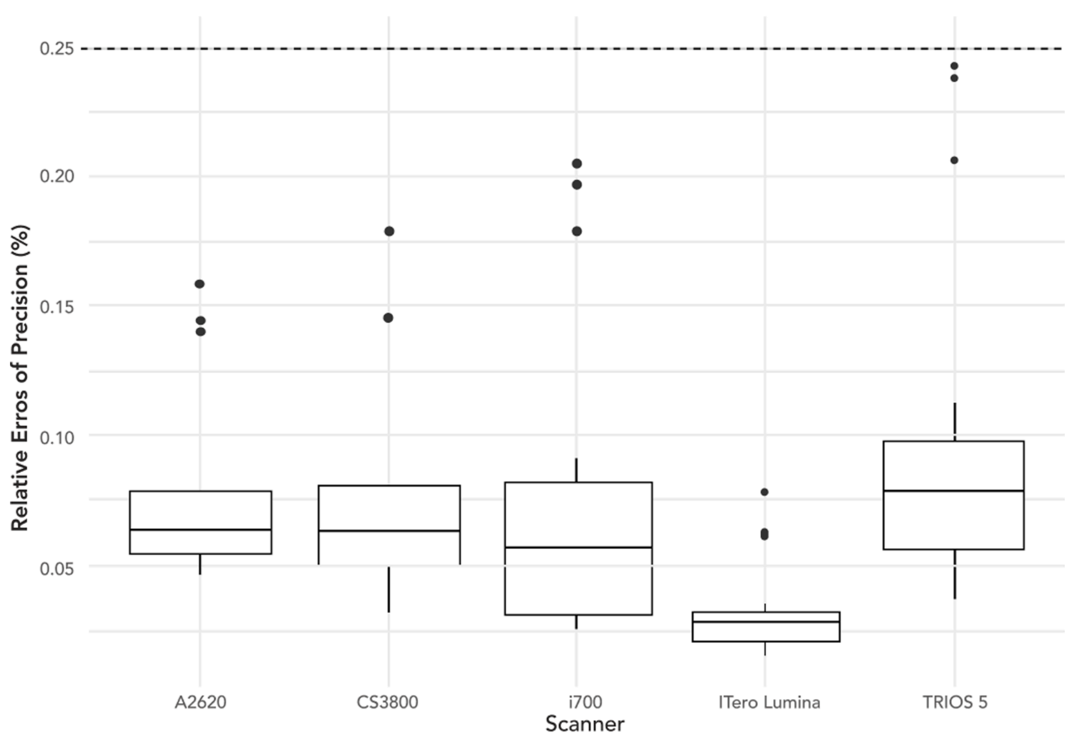

Fig. 3. shows the relative error of precision, representing consistency across repeated measurements. Precision ranged from 0.015 % to 0.24 %, with a 95 % CI of 0.024 % to 0.12 %). The Lumina scanner delivered the highest number of acceptable scans across all tested conditions.

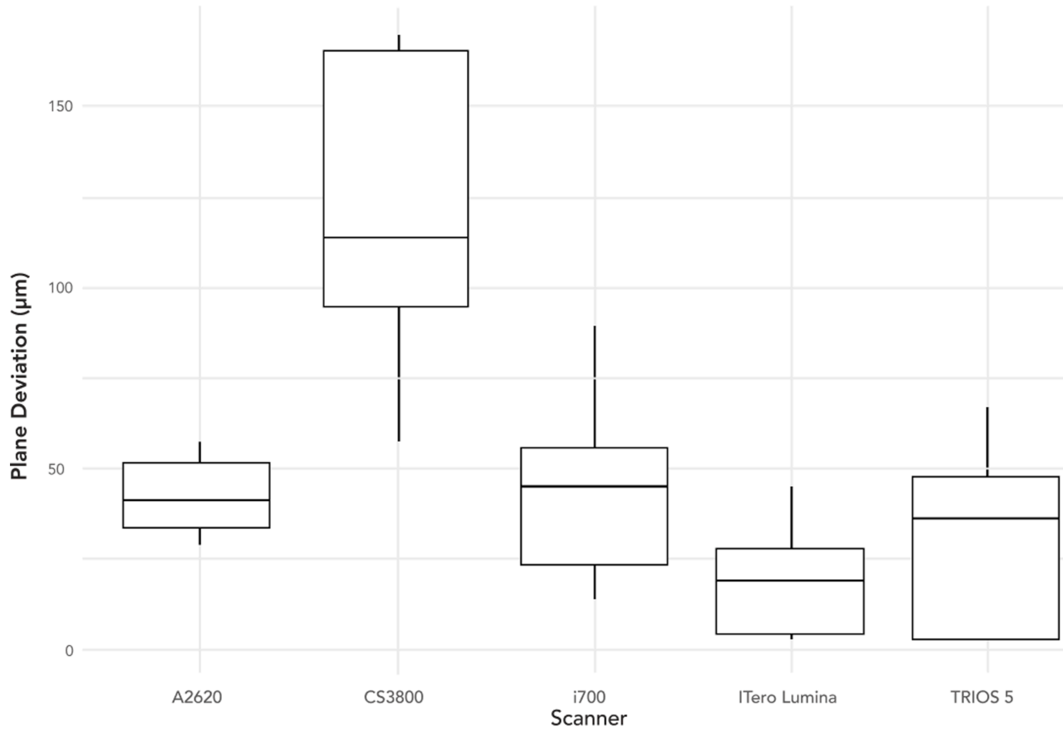

Fig. 4. Plane deviation by scanner (µm). Top of the box (upper hinge) represents the 75th percentile, and bottom of the box (lower hinge) represents the 25th percentile. Whiskers represent the maximum and minimum values.

Table 5
Tukey's multiple comparisons of mean plane deviations.

Scanner	P-value
AS260-Lumina	0.17
CS3800-Lumina	<0.0001
i700-Lumina	0.12
TRIOS5-Lumina	0.70
CS3800-AS260	<0.0001
i700-AS260	0.99
TRIOS5-AS260	0.86
i700-CS3800	<0.0001
TRIOS5-CS3800	<0.0001
TRIOS5-i700	0.77

P-value: Indicates the statistical significance of each scanner's pair comparison. A p-value below 0.05 suggests that the difference in precision is statistically significant.

conventional techniques [19–22]. However, for extensive restorations—spanning five or more units or full arches, including natural teeth and implants—digital impressions show reduced accuracy compared to traditional methods [23–26], setting the stage for the development and testing of new technologies like MDC in this study.

MDC technology introduced in 2024 decouples the connection between scanner FOV and wand size allowing for an increased maximal FOV compared to the other tested scanners in this study [11,39–42]. This study is the first to evaluate the full-arch accuracy of a scanner using MDC technology, namely the iTero Lumina. Results indicated statistically significant differences among the tested scanners in terms of linear relative errors in both trueness (Lumina 0.04 %, i700 0.071 %, AS260 0.074 %, CS3800 0.089 %, TRIOS5 0.14 %) ($p < 0.0001$) and precision (Lumina 0.032 %, CS3800 0.073 %, i700 0.074 %, AS260 0.077 %, TRIOS5 0.1 %) ($p < 0.01$). The findings support the null hypothesis, indicating that MDC technology may provide improved long-span accuracy compared to conventional scanners utilizing rear illumination. However, given the limited clinical evidence and the novelty of this technology, further research is warranted to substantiate these findings. Accuracy consists of trueness and precision, trueness refers to the closeness of test results to the true or accepted reference value, while precision is the closeness between repeated test results [27]. All scanners assessed in this study demonstrated mean relative errors of trueness of <0.25 % of the scanned distance, a threshold established by the ADA/ANSI 132 guidelines as clinically acceptable for long-span digital intraoral imaging. Lumina scanner delivered the highest ratio of acceptable scans, 99.6 % across all tested conditions.

Adherence to an internationally recognized standard, ANSI/ADA Standard 132, was pivotal in the design and methodology of this study. This standard provides a rigorous framework for evaluating IOS performance ensuring consistency, reliability, and clinical relevance. Standardized benchmarks enable researchers and manufacturers to produce credible and comparable data, thereby fostering confidence among clinicians, researchers, and regulatory bodies. This consistency is critical to advance the adoption and refinement of scanning technologies in clinical practice.

The methods employed in this study align with those used in prior research on IOS full-arch performance, adhering to the ADA/ANSI 132 framework. However, this study used relative error to report accuracy, departing from the absolute error approach of previous investigations, such as Treesh et al. [28], Kwon et al. [29], and Cui et al. [30], which reported deviations in micrometers. This choice underscores a focus on proportional accuracy across varying spans, providing a standardized metric tailored to the clinical demands of full-arch IOS evaluation. Unlike absolute error, which offers a fixed measure but lacks scalability, relative error, expressed as a percentage, ensures contextually relevant consistency and enables direct comparison with studies like Pattamavilai et al. [31]. Pattamavilai et al. [31] evaluated the trueness and precision of three IOS under the ADA/ANSI 132 framework, testing various scan patterns. A well-designed scan pattern seeks to ensure sufficient overlap between consecutive images, critical for accurate software stitching and minimizing errors. Their findings revealed that scan patterns significantly affect trueness and precision, while this

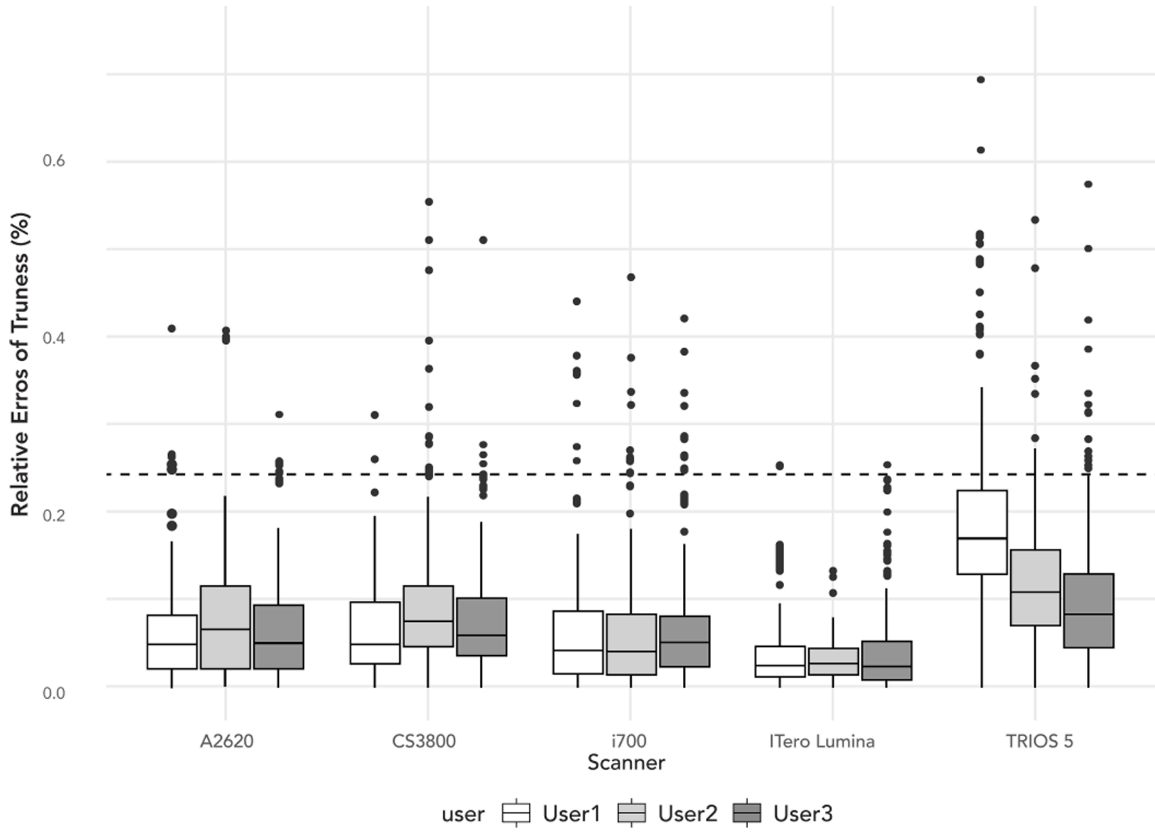

Fig. 5. Inter-operator variability comparison of relative error of trueness. Top of the box (upper hinge) represents the 75th percentile, and bottom of the box (lower hinge) represents the 25th percentile. Whiskers represent the maximum and minimum values. Circles, outliers.

study's reliance on manufacturer-recommended patterns demonstrated improved trueness for Lumina, likely due to MDC's reduced dependence on stitching. The trueness of the TRIOS scanner reported by Pattamavilai et al. (0.16 %) closely matches this study's TRIOS5 result (0.14 %), further validating the reliability of this evaluation approach.

If the ADA/ANSI 132 standard acceptance criteria serve as the threshold between clinically acceptable and unacceptable outcomes, it can be hypothesized that the proportion of clinically acceptable scans is inversely correlated with the frequency of retakes and remakes. Repeat or retake analysis, a concept borrowed from radiology, is a quality assurance measure designed to evaluate and minimize the number of repeated imaging procedures. This analysis typically involves categorizing rejected images based on their causes, such as equipment limitations, operator errors, or patient-related factors [32]. In the context of this study, improving the ratio of acceptable scans may reduce retakes by addressing current equipment limitations. By reducing the number of retakes, dental practices can minimize patient discomfort, improve the overall patient experience, and reduce the time and costs associated with repeating laboratory and clinical procedures.

Although the level of accuracy reported in this study is adequate for most tooth- and soft-tissue-borne restorations, the literature increasingly highlights the need for greater precision in addressing the unique challenges of full-arch implant-borne restorations [18,33–35]. In addition, implant prosthodontics introduce complexities beyond global accuracy. Factors, such as scanning body mesh congruence with digital library files, affect implant precision, underscoring the need for a comprehensive evaluation framework that integrates global and implant-specific metrics [36]. Future research should explore the accuracy of MDC technology in implant-borne restorations and its potential role in improving long-term treatment success.

This study's exploration of plane deviation and inter-operator variability, offers additional insights into IOS full-arch performance beyond linear accuracy metrics. Plane deviation results showed Lumina with a mean of 19 μm error compared to 33–120 μm for other scanners, yet these differences lacked statistical significance ($p > 0.05$), suggesting that planar accuracy may require larger sample sizes or more complex models to detect meaningful variations. Similarly, inter-operator variability indicated Lumina's consistency across users with lower standard deviations than AS260 or TRIOS5, though statistical significance was not established. These findings echo Treesh et al. [28], where operator variability influenced precision without clear statistical differentiation, and Pattamavilai et al. [31], who noted pattern execution effects without isolating operator impact. While MDC technology's design may contribute to these observations by reducing stitching and technique sensitivity, the lack of significance tempers conclusions. Future research could refine these assessments, exploring their clinical relevance in diverse operator and anatomical contexts.

Our study highlights the potential impact of IOS FOV on the accuracy of digital impressions. A larger FOV allows capture of broader oral cavity sections in one scan, reducing reliance on multiple overlapping scans and subsequent image stitching—processes prone to cumulative errors [5]. Desktop scanners, for instance, owe their superior performance to an expansive FOV, enabling extensive areas to be recorded in a single frame, thus minimizing operator involvement and boosting precision and reliability [3,30]. Typically, IOS scan heads are engineered for compactness to ensure smooth intraoral movement; in traditional scanners, this design limits FOV, and as the scanned area grows, stitching demands intensify, potentially compromising accuracy [37,38]. The decoupling of FOV from wand dimensions by MDC technology is a shift from conventional IOS limitations, suggesting that future intraoral scanners could achieve desktop-scanner-level precision while preserving ergonomic compact wand designs—a prospect warranting exploration. Beyond merely enlarging FOV, MDC's multi-camera and multi-projector system has the potential to free FOV geometry from the rigid rectangular constraints of rear-illumination scanners. This flexibility, enabled by mounting the optical components at the wand tip, could support future designs with the ability to capture the entire dental arch in a seamless sweep, bypassing the incremental stitching required by existing IOS. Unlike traditional IOS, constrained by wand ergonomics and rectangular light projection, adaptable FOV geometry might conform to the oral cavity's natural curvature, enhancing accuracy in regions like posterior molars or anterior incisal edges. This development points to a future where IOS may surpass desktop scanner performance clinically. Future studies should assess designs leveraging this geometric freedom, evaluating their feasibility for single-frame full-arch capture and effects on scan duration, operator efficiency, and patient comfort.

The findings of this study were based on a specific sample size and set of conditions. A more diverse sample could provide a more comprehensive understanding of scanner performance. In addition, the measurements were performed under controlled conditions that may differ from those in real-world clinical environments. While the controlled environment ensured precision in reference measurements, it excluded variables like saliva, tissue mobility, and patient movement, which could disproportionately affect scanners with smaller FOVs reliant on extensive stitching.

5. Conclusions

This in vitro study indicated that intraoral scanner acquisition technology influences full-arch digital impression accuracy, with MDC technology demonstrating lower linear relative errors in trueness and precision compared to confocal and structured-light technologies. However, considering the controlled nature of the study and the limited clinical evidence available for newer technologies, further validation is required to determine the relevance of these findings in clinical practice.

Disclosure statement

This study was sponsored and financed by Align Technology, Ltd., manufacturer of the iTero Lumina scanner.

CRediT authorship contribution statement

Ingo Baresel: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jens Baresel:** Writing – review & editing, Investigation, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Dr. Ingo Baresel reports financial support was provided by Align Technology, Inc. Dr. Ingo Baresel reports a relationship with Align Technology, Inc. that includes: consulting or advisory. Dr. Ingo Baresel reports a relationship with Medit that includes: consulting or advisory. Dr. Ingo Baresel reports a relationship with Shining 3D that includes: consulting or advisory. Dr. Ingo Baresel reports a relationship with 3Shape that includes: consulting or advisory. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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