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Trueness and precision of complete arch dentate digital models produced by intraoral and desktop scanners: An *ex-vivo* study

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ABSTRACT

Objectives: The study aimed to compare the trueness and precision of five intraoral scanners (Emerald S, iTero Element 5D, Medit i700, Primescan, and Trios 4) and two indirect digitization techniques for both teeth and soft tissues on fresh mandibular and maxillary cadaver jaws.

Methods: The maxilla and mandible of a fully dentate cadaver were scanned by the ATOS industrial scanner to create a master model. Then, the specimens were scanned eight times by each intraoral scanner (IOS). In addition, 8 polyvinylsiloxane (PVS) impressions were made and digitized with a Medit T710 desktop scanner. Stone models were then poured and again scanned with the desktop scanner. All IOS, PVS, and stone models were compared to the master model to calculate the mean absolute surface deviation for mandibular teeth, maxillary teeth, and palate.

Results: For mandibular teeth, the PVS trueness was only significantly better than the Medit i700 ($p < 0.001$) and Primescan ($p < 0.05$). In maxillary teeth, the PVS trueness was significantly better than all IOSs ($p <$ 0.05–0.001); the stone trueness was significantly better than Emerald S ($p < 0.01$), Medit i700 ($p < 0.001$) and Primescan ($p < 0.01$). In the palate, PVS and stone trueness were significantly lower than the iTero Element 5D ($p < 0.01$) and Trios 4 ($p < p < 0.01$). Stone trueness was significantly lower than the Medit i700 ($p < 0.05$). The precision in the palate was significantly lower for PVS and stone than for Emerald S ($p < 0.01$, $p < 0.05$), iTero Element 5D ($p < 0.01$, $p < 0.01$), Primescan ($p < 0.001$, $p < 0.001$), and Trios 4 ($p < 0.001$, $p < 0.01$). Significant differences in trueness between the IOSs were observed only in the mandibular teeth. The Medit i700 performed worse than Emerald S ($p < 0.01$) and iTero Element 5D ($p < 0.01$). For mandibular teeth, the Medit i700 was significantly more precise than Primescan ($p < 0.01$) and the Emerald S ($p < 0.05$). The Trios 4 was significantly less precise than Emerald S ($p < 0.05$). The precision of Medit i700 was significantly worse than iTero Element 5D ($p < 0.01$) for maxillary teeth, as well as the Primescan ($p < 0.01$) and Trios 4 ($p < 0.05$) for the palate.

Conclusions: In general, indirectly digitized models from PVS impressions had higher trueness than IOS for maxillary teeth; precision between the two methods was similar. IOS was more accurate for palatal tissues. The differences in trueness and precision for mandibular teeth between the various techniques were negligible.

Clinical significance: All investigated IOSs and indirect digitization could be used for complete arch scanning in mandibular and maxillary dentate arches. However, direct optical digitization is preferable for the palate due to the low accuracy of physical impression techniques for soft tissues.

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1. Introduction

The beginnings of digital data acquisition in dentistry can be traced back to the first use of computer-aided design/computer-aided manufacturing (CAD/CAM) by Dr. Francois Duret in 1971 [1]. Other European innovators subsequently developed dental CAD/CAM technology, leading to the first commercially available system in 1985 with CEREC [2,3]. Digital data acquisition in the laboratory started in the 1980′s as well, with the development of the Procera system to fabricate alumina copings [2]. These systems laid the foundation for digital restorative solution fabrication. The modern laboratory of today could not operate without digital scanning and CAD/CAM, with most restorations generated via digital workflows [4]. Meanwhile, the use of an intraoral scanner (IOS) continues to increase in clinical practice [5].

Per ISO standard 5725-1, the accuracy of a measurement method consists of a combination of trueness and precision [6]. Trueness is defined as deviation from the actual dimensions of a measured object. In this case, trueness is how close an IOS creates a virtual model compared to the standard reference (i.e., master) model created by an accurate industrial scanner. Precision is defined as how close measurements are to each other for the same measuring device. A practical and commonly used measure of precision is the experimental standard deviation. The accuracy of IOS systems varies amongst different scanners [7–10]. Previous studies have shown IOS trueness and/or precision to be affected by numerous variables, including operator experience [11], the substrate being scanned [12,13], and the scan pattern used [14–16]. Choosing the appropriate material for the reference standard model (such as metal, plastic typodont, or cadaver) is crucial, as the optical reflectance of the substrate plays a significant role in determining the accuracy of the optical impression [13,17].

In the management of single unit restorations, the use of an IOS for data acquisition provides significant benefits over traditional analog impressions. For example, physical impression materials and resultant stone models have inherent limitations leading to unavoidable inaccuracies [18], which IOS systems can potentially overcome [19]. IOS also eliminates several issues with physical impressions, including their limited window of usability, needed space for storage, and the requirement to physically send the impression/models to and from the laboratory [20]. The use of an IOS reduces the time needed to fabricate a restoration and is preferred by both patient and operator over traditional analog impressions [19,21]. Several systematic reviews and meta-analyzes have already confirmed that single unit restorations fabricated via digital workflows provide restorations that fit as good or better than those fabricated traditionally [22]. Even materials usually associated with casting or pressing techniques can significantly benefit from the introduction of CAD/CAM-driven milling [23] and 3D printing [24].

Early IOS systems were best for quadrant scanning, losing significant accuracy when applied to full arch scanning. A smaller field of view (one to three teeth) inherently limited the ability of these scanners to provide accurate full arch models [19,25,26], given these models are created through the "stitching" of overlapping data sets captured by the IOS [15,26]. These difficulties are even more pronounced when capturing long span edentulous areas and movable mucosa, thanks to a lack of well-defined anatomical landmarks [27–29]. Improvements in IOS hardware and software have been documented to significantly improve the accuracy of dentate full arch scanning [13]. Indeed, an earlier study found digital scans to exhibit better trueness than alginate or polyether impressions for complete dentate arches but fell short of polyvinylsiloxane (PVS) [30]. Yet a more recent study using a fresh maxillary cadaver and seven different IOS systems found several systems to perform as well as the PVS group with regards to trueness and precision [31]. These improvements are reflected in literature pertaining to soft tissue scanning as well. Recent studies have shown IOS systems capable of producing results that meet or exceed the accuracy of analog impressions for capturing palatal tissues [31,32], creating removable partial denture frameworks [33] and implant-related restorations in partially and fully edentulous scenarios [34,35].

While PVS and stone haven't significantly changed in the last twenty years, digital scanners are in a constant state of change. As IOS systems and desktop scanners evolve, it is necessary to periodically re-evaluate their capabilities, using a standard reference model as clinically relevant as possible. The aim of this study was to evaluate the trueness and precision of complete arch dentate digital models of a human cadaver's jaws created directly by five different IOS systems and indirectly by scans of PVS impressions and stone models with a laboratory desktop scanner. The secondary aim of the study was to evaluate whether tissue substrate (i.e., tooth, soft tissue) affected the accuracy of the impression. The null hypothesis was that neither the type of digital workflow used nor the tissue substrate would affect the trueness and precision of the digital models.

2. Materials and methods

2.1. Preparation of the test specimens

A fresh cadaver specimen without embalming was obtained. It was stored at 4 °Celsius until the study, and the specimen was brought to room temperature. The cadaver comprised fully dentate arches with intact, complete dentition on both the mandible and maxilla (Fig. 1.). The methods were followed from previously published studies [11,26,36,37]. The scanning environment was kept cool at a high humidity level to ensure the cadaver specimen did not start to decompose and replicate a moist oral environment. The teeth were either natural teeth or had amalgam restorations.

2.2. Scanning procedures

The cadaver jaws were scanned to create a master reference model using the ATOS Capsule Scanner (GOM, Braunschweig, Germany) by an industrial scanning company (3D Systems Manufacturing, Rock Hill, SC, USA). This scanner exhibits trueness of 5 μm and precision of 2 μm [38,39]. The master scan is considered the negative control in this study.

The mandibular arch and maxillary arch, including the palate, were scanned by five IOSs: Trios 4 (software version 21.2.0, 3Shape, Copenhagen, Denmark), CEREC Primescan (software version 5.2, Dentsply Sirona, NewYork, PA, USA), Medit I700 (software version 2.4.4, Medit Crop, Seoul, Korea), iTero Element 5D (iTero Workflow 2.0, Align Technology, Tempe, Arizona), and Planmeca Emerald S (software version 6.3.2, Planmeca, Helsinki, Finland). A calibrated user with at least one year of experience with the corresponding scanner completed eight-eight full arch scans with each particular IOS following the manufacturer recommended scanning pattern.

Following the IOS scans, eight conventional impressions were made by a prosthodontist following manufacturer recommendations. The impression was made with PVS (Reprosil, Dentsply Sirona, NewYork, PA, USA), using light body wash on the teeth and a medium body viscosity loaded in the tray. The PVS impressions were scanned by a Medit T710 desktop scanner (Medit Crop, Seoul, Korea). One physical impression of the palate was damaged, and the results were removed from the data analysis. The impressions were then poured in low expansion die stone (Silky Rock Whip Mix Louisville, KY) using a vacuum mix (Whip Mix Louisville, KY). The 15 stone models were also scanned with the Medit T710.

2.3. Measurement of the trueness and precision

The scans from each IOS, desktop scanner, and industrial scanner were exported in the format of standard tessellation language (STL) using the highest quality settings from each scanner. The STL files were imported into the metrology software Geomagic Control X (3D Systems, Santa Ana, CA, USA). The maxillary model was segmented into teeth and

Fig. 1. Maxillary and mandibular cadaver specimens that were used in the study.

palate using the re-segmentation tool (Fig. 2A and B). The mandibular master model was segmented into teeth (Fig. 2C). This segmentation ensures that the alignment algorithms and deviation measurement are limited to the areas of interest.

Each STL file of the experimental scans was superimposed onto the master model using an Initial Alignment and a best-fit alignment, using the hard tissue as the reference for the alignment. The software used an iterative closest point algorithm in the Best Fit Alignment function to align the experimental group scans to the master scan. The deviation between the two aligned scans was calculated by the absolute mean of the negative and positive distances between the two surfaces and expressed as the mean absolute distance (MAD). The trueness between impression groups and areas was compared using the means of the groups. Whereas the precision was evaluated by comparing the standard deviation of each group (impression and areas).

2.4. Statistics

In a previous study [31], the trueness of eight scanners was compared in a cadaver. The pooled SD was 6 for maxillary teeth and 29 for palate. Considering alpha=0.05 and a power of 0.80, the calculations revealed that 8 specimens per group would be needed to detect a 10 µm difference in teeth and 50 µm on the palate (G*power (University of Düsseldorf, Düsseldorf, Germany) using a non-parametric test.

The data in the graphs and text are given as median and first and fourth quartiles. The MAD values were analyzed for normality by Shapiro-Wilk test. Statistical comparisons of trueness MAD values were made by the non-parametric Kruskal-Wallis test. The precision was estimated by the experimental standard deviation. The precision of the groups was statistically compared by the F-test. The $p < 0.05$ was accepted for pairwise comparison to reject the null hypothesis after Holm's Sequential Bonferroni adjustment for multiple pairs. All analyzes were done in SPSS statistical software (version 28, IBM).

3. Results

3.1. Effect of the digitization method on the trueness

The descriptive statistics and the pairwise comparison are shown in Table 1.

For mandibular teeth, the PVS had significantly better trueness than Medit i700 and Primescan (Fig. 3.). The Emerald S and iTero Element 5D had significantly better trueness than Medit i700.

For maxillary teeth, the PVS had significantly better trueness than all IOSs, but not better than the stone. Additionally, the stone was better than Emerald S, Medit i700, and Primescan. No differences were found between IOSs.

In the palate, the iTero Element 5D and Trios 4 had significantly better trueness than PVS and stone. The Medit i700 had significantly better trueness than the stone. No differences were found between IOSs.

3.2. Effect of the digitization method on the precision

The descriptive statistics and the pairwise comparison are shown in Table 2.

In mandibular teeth, the PVS had significantly better precision than Emerald S, iTero Element 5D, Primescan, and stone. The Medit i700 and Trios 4 had significantly better precision than Emerald S and Primescan.

In maxillary teeth, the PVS and iTero Element 5D had significantly better precision than Medit i700.

In the palate, the PVS and stone had significantly lower precision than Emerald S, iTero Element 5D, Primescan and Trios 4. The

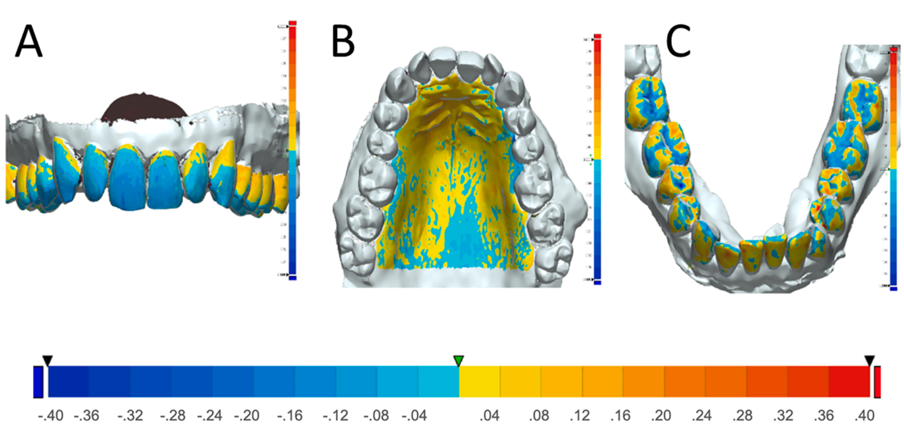

Fig. 2. The color-coded map generated after the Best Fit Alignment algorithm shows the local deviation. The upper and lower limits were set at ±0.5 mm. Darker blue highlights indicated a negative or inward deviation and darker red highlights indicated a positive or outward deviation of the test model. The teeth (A) and the palate (B) are segmented in the maxillary arch. The teeth are segmented in the mandibular arch (C).

Table 1
The significant differences in trueness (μm) between digitalization methods.

		N	Mean	Median	Q1	Q3	Emerald S	iTero Element 5D	Medit i700	Primescan	Trios 4	PVS	stone
mandibular teeth	Emerald S	8	33	29	29	38			**				
	iTero Element 5D	8	32	29	29	35			**				
	Medit i700	8	42	42	40	44	**	**				***	
	Primescan	9	40	37	35	41						*	
	Trios 4	8	33	33	31	36							
	PVS	9	30	30	29	30			***	*			
	stone	8	35	34	32	38							
maxillary teeth	Emerald S	8	50	49	47	52						***	**
	iTero Element 5D	8	48	47	46	49						**	
	Medit i700	8	54	51	47	58						***	***
	Primescan	8	51	51	46	53						***	**
	Trios 4	9	44	43	37	51						*	
	PVS	8	28	26	25	30	***	**	***	***	*		
	stone	8	33	31	29	36	**		***	**			
palate	Emerald S	8	57	56	54	60							
	iTero Element 5D	8	49	50	46	53						**	**
	Medit i700	8	54	52	43	60							*
	Primescan	7	57	57	55	61							
	Trios 4	9	49	50	43	52						**	**
	PVS	7	85	89	71	101		**			**		
	stone	7	91	98	80	109		**	*		**		

* indicate significant differences between scanners,.
[*] $p < 0.05$,.
[**] $p < 0.01$,.
[***] $p < 0.001$.

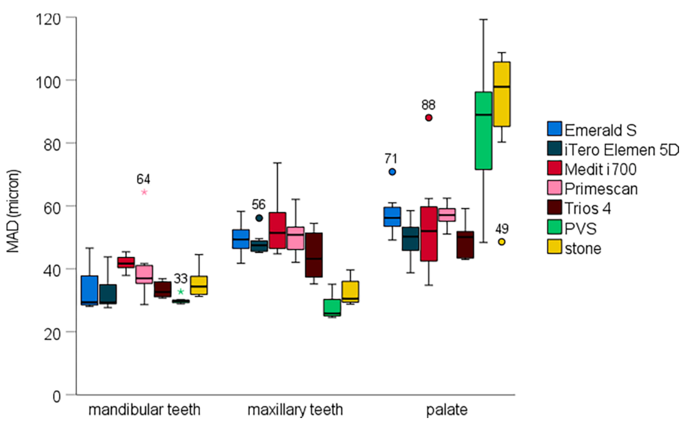

Fig. 3. Comparison of the trueness between digitalization methods in different areas. The mean absolute distance (MAD in micrometers) was calculated after the alignment of the test scan with the master scan. Single dots depict the outliers with the MAD values above them.

Primescan and Trios had significantly better precision Medit i700 .

3.3. *Effect of the scanned area on the trueness*

PVS and stone had significantly better trueness for the mandibular teeth and maxillary teeth than the palate (Fig. 4.). iTero Element 5D ($p < 0.05$), Medit i700 ($p < 0.01$), and Trios 4 ($p < 0.05$) had significantly better trueness in the mandible than in the maxilla. Emerald S ($p < 0.001$), iTero Element 5D ($p < 0.001$), Medit i700 ($p < 0.05$), and Trios 4 ($p < 0.001$) had significantly better trueness for the mandibular teeth than the palate. No significant difference was found between maxillary teeth and the palate for IOSs.

3.4. *Effect of the scanned area on the precision*

PVS and stone had significantly ($p < 0.001$) better precision for the mandibular and maxillary teeth than the palate. PVS had also better precision ($p < 0.01$) for the mandibular teeth than the maxillary teeth.

Medit i700 ($p < 0.001$) and Trios 4 ($p < 0.01$) had significantly better precision in the mandible than in the maxilla. Medit i700 ($p < 0.001$) had significantly better precision for the mandibular teeth than in the palate. Contrarily, Primescan ($p < 0.05$) had significantly better precision in the palate than for mandibular teeth. No significant difference was found between maxillary teeth and the palate for IOSs.

4. Discussion

There were significant differences in accuracy between scanners, digitization methods and substrate being scanned, thus partially rejecting the null hypothesis.

For maxillary teeth, the indirect digitization method (PVS and stone) exhibited significantly better trueness than the investigated IOSs. However, precision was similar for both methods, except for the Medit i700, which was significantly less precise. These results are consistent with several previous investigations [30,40], that found stone models poured from PVS impressions to have better trueness than digital models created from intraoral scans. In contrast to those studies, the current investigation found all but the Medit i700 to have a level of precision equal to that of the digitized stone model. This could be explained by continued improvement of software algorithms over time. A more recent study [31] using a similar methodology to the current one found no difference in the accuracy of seven different IOS systems compared to a digitized stone model. The discrepancy in these results is likely due to the difference in desktop scanners used for digitization of the stone model. In parallel to IOSs, desktop scanners have undergone significant improvements in recent years. The desktop scanner used in the previous study has a documented trueness and precision for the maxillary arch of 46 μm and 69 μm, respectively [41]. The desktop scanner used in the current investigation has a documented trueness of 12–16 μm and precision of 3–4 μm [39]. Another recent study using a newer desktop scanner also found the trueness of a scanned PVS impression significantly better than an intraoral scan, while being similar in precision [42]. In contrast to the present study, it found the scanned stone model similar to the IOS in terms of trueness, while being less precise. The variability in outcomes between these two studies could be a result of using different desktop scanners, different dental stone, and/or different substrates (intact vs. prepared teeth).

In contrast to the maxillary arch, the difference in accuracy between

Table 2
The significant differences in precision (μm) between digitalization methods. I think we need a legend on what the different asterisk mean.

		Standard Deviation	Emerald S	iTero Element 5D	Medit i700	Primescan	Trios 4	PVS	stone
Mandibular teeth	Emerald S	7.1			*		*	***	
	iTero	5.6						***	
	Medit i700	2.5	*			**			
	Primescan	10.1			**		**	***	
	Trios 4	2.5	*			**			
	PVS	1.2	***	***		***			***
	stone	4.5						***	
Maxillary teeth	Emerald S	5.1							
	iTero	3.6			**				
	Medit i700	9.7		**				*	
	Primescan	6.2							
	Trios 4	7.4							
	PVS	3.8			*				
	stone	4.2							
Maxillary palate	Emerald S	6.5						**	*
	iTero	6.1						**	**
	Medit i700	16.4				**	*		
	Primescan	3.8			**			***	***
	Trios 4	5.6			*			***	**
	PVS	23.0	**	**		***	***		
	stone	21.3	*	**		***	**		

* indicate significant differences between scanners,.
[*] $p < 0.05$,.
[**] $p < 0.01$,.
[***] $p < 0.001$.

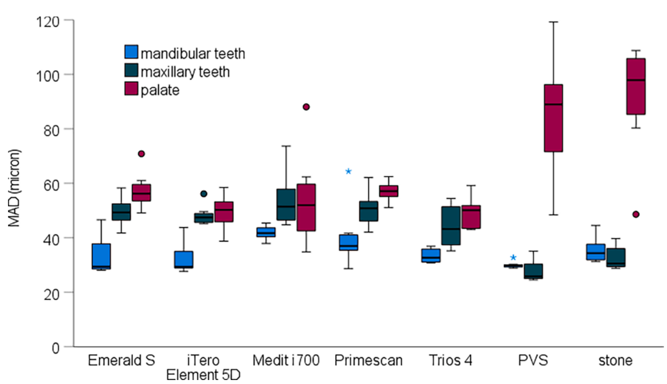

Fig. 4. Comparison of the trueness between different areas in digitalization methods. The mean absolute distance (MAD, in micrometers) was calculated after the alignment of the test scan with the master scan.

the direct and indirect digitization methods was negligible for mandibular teeth. The IOSs had significantly better trueness for the mandibular arch than the maxillary arch, equaling that of PVS and stone. These findings are consistent with another recent study [42], which saw similar trends and outcomes. With regards to precision, PVS and some IOSs performed better than other IOSs and stone. Gao and colleagues [42] found the same lack of precision for mandibular stone models, with their stone group significantly less precise than PVS and IOS.

The IOSs tested performed equally well in capturing the palatal soft tissue and the dentition, both in terms of trueness and precision. Meanwhile, PVS and stone showed higher deviations for soft tissue, performing significantly worse than the IOSs. These findings contrast with those of two clinical studies that found the Trios 3 scanner to have lower trueness for the palate than the dentition [43,44]. However, in those studies the reference model was a poured stone model from a PVS impression, scanned by a desktop scanner. In the present investigation, the actual maxilla was scanned by a highly accurate industrial scanner, providing a much better reference model. What is apparent from these studies, as well as one from Mennito and colleagues [31], is that PVS impressions of soft tissues can have significant inaccuracies, likely due to the compression of tissues that is unavoidable when making a physical impression. Similar results to the current study have been documented with fully edentulous maxillary intraoral scans and digitized polysulfide impressions [45], with the intraoral scans exhibiting significantly better trueness and precision.

Few significant differences were observed between the investigated IOSs, with trueness values varying by less than 12 μm and precision values varying less than 13 μm for any given substrate. It is reasonable to assume this narrowing of differences between IOSs of different manufacturers reflects continued improvements in scanner hardware and software, as documented in previous investigations [13,46]. For teeth, the worst individual scan for all scanners was below 75 μm with respect to trueness, which is similar to other research [13,16,25,31]. While the median trueness values differ from some of these previous studies, this is to be expected, given the heterogeneity in hardware/software used, variations in reference model creation and differences in evaluated substrate.

The current study used highly experienced practitioners for each of the specific IOS systems, along with a highly accurate and clinically relevant reference model. Despite these efforts, certain inherent limitations and challenges exist. Multiple factors have been shown to affect the accuracy of digital scans, including tooth type [47], substrate [13,48], the type of tooth preparation [49], arch width and geometry [50], and scanning strategy [14–16]. While perhaps less influential with newer IOS models, the experience of the one scanning also affects accuracy. The use of different, highly experienced operators for each IOS to ensure excellent intra-system performance in this study could be seen as a type of limitation, given possible variability between operators in their abilities and scan pattern used. Another limitation of this study, as with any study of this type, is that the results apply only to the systems and clinical scenario tested and may not be generally applicable to other systems and/or clinical scenarios. Furthermore, while actual human jaws were used, the study did not replicate all factors that could affect IOS accuracy *in vivo*, including things like patient movement, the presence of the tongue and saliva, and patients with limited opening. As technologies and techniques evolve, further research in these areas is of upmost importance to evaluate and validate them with respect to ensuring quality patient outcomes.

5. Conclusions

Within the limits of this study, the direct and indirect digitization methods produced models of equal accuracy for mandibular teeth. For maxillary teeth, both methods were equally precise, with the indirectly digitized PVS models exhibiting higher trueness. IOS scans produced more accurate models for palatal tissues. Differences in trueness and precision between IOS systems were minimal.

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CRediT authorship contribution statement

Janos Vag: Visualization, Validation, Writing – original draft. **Clinton D. Stevens:** Validation, Writing – original draft, Writing – review & editing. **Mohammed H. Badahman:** Investigation. **Mark Ludlow:** Investigation. **Madison Sharp:** Investigation. **Christian Brenes:** Investigation. **Anthony Mennito:** Investigation. **Walter Renne:** Conceptualization, Investigation, Project administration, Supervision, Writing – original draft, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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