EVALUATION OF THE ACCURACY OF 5 DIGITAL INTRAORAL SCANNERS: IN VITRO ANALYSIS USING 3-DIMENSIONAL COMPUTERIZED METROLOGY

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A thesis submitted to the faculty at the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in the Adams School of Dentistry (Prosthodontics).

Chapel Hill
2020

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ABSTRACT

Ryan E. Abbott: Evaluation of the Accuracy of 5 Digital Intraoral Scanners: In Vitro Analysis Using 3-Dimensional Computerized Metrology
(Under the direction of Ryan Cook)

Purpose: To evaluate precision and trueness of 5 dental intraoral scanners.

Materials: Mixed material master cast. 5 types of scanners, 5 scans per machine. Compare test scans with master scan using software. Statistically examine precision and trueness. Scanners: iTero Element, iTero Element 2, 3Shape TRIOS, 3Shape TRIOS 3, Dentsply Sirona Primescan. Master scanner: GOM ATOS Core 135. Software: GOM Inspect.

Results: Posterior Sextant: Primescan had best precision. Anterior Sextant: TRIOS 3 had best trueness and precision. CoCr Crown: Element and Element 2 had best trueness and precision. Full Arch (Telio CAD): TRIOS 3 had best trueness. Cross-Arch distance: Element 2 had best trueness. CoCr crown adjacent to Telio CAD: Primescan had best trueness, Element had best precision. PEEK scanbody adjacent to Telio CAD: TRIOS 3 had best trueness.

Conclusions: Tested scanners can be appropriate for clinical use. Although clinicians may focus on trueness, bigger differences may be in precision.

To my wife, who concurrently completed an unseen residency

and whose certificate is written on our children's hearts.

ACKNOWLEDGEMENTS

I would like to thank Dr. Ryan Cook for his enthusiastic, knowledgeable, and insightful mentorship during my residency at the University of North Carolina Adams School of Dentistry. He has provided leadership through joyous and tumultuous times, helping to make it 3 years I will always treasure and never forget. Likewise, my co-residents, Jackson Blackburn, Chris Castelin, and Tessa Kim, as well as so many in overlapping graduating classes and related graduate programs, who humbled me with their intelligence and hard work; and many pre-doctoral dental students with whom I had the opportunity to work in the pre-clinic and clinic, who inspired me with their youthful enthusiasm and showed me the bright future of our profession.

Drs. Ibrahim Duqum, Wendy Clark, and Donald Tyndall provided tireless feedback as my thesis progressed, and I am grateful for their examples as dentist-educators. Likewise, Drs. Dan Bailey and Kent Healey helped inspire me to come to UNC and gave so much of their precious time in retirement to mentor me and my resident colleagues in the rich art and traditions of the Prosthodontic profession.

Brandon Penrod at Capture 3D Inc. of Cornelius, North Carolina and his ingenious team of engineers made it possible for me to obtain the master scans and metrology software on a University budget and timeframe.

Lisa Munsey of Dentsply Sirona and the fantastic team at the Dentsply Sirona Academy in Charlotte, North Carolina generously gave me access to Primescan scanners for data collection, as these were not available at the University.

Dr. Ceib Phillips and Pooja Saha helped enlighten for me the world of biostatistics and provided critical statistical analysis for the project. Their timely consultation and analysis were indispensable.

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LIST OF ABBREVIATIONS

CAD	Computer-Aided Design
CoCr	Cobalt chromium alloy
IOS	Intra-Oral Scanner / Scanners
PEEK	Poly(EtherEtherKetone) polymer
PMMA	Poly(methylmethacrylate) resin
PVS	Poly(vinyl siloxane), addition reaction silicone impression material
SLM	Selective Laser Melting, a metallic additive manufacturing process
STL	Standard Tessellation Language
UDMA	Urethane dimethacrylate resin

INTRODUCTION

The digital Intra-Oral Scanner (IOS) is a current area of technological development in dentistry. Digitization of the fabrication of indirect restorations can lead to improved efficiency in the dental laboratory, and digital workflows represent the major growth segment in the dental laboratory industry worldwide. (1) Intraoral scanning can bring some of the benefits of digitized workflow to the clinic, with studies finding adequate accuracy comparable to conventional impressions and potential for improved patient comfort and operator preference. (2) Intraoral scanning also can eliminate the need for cast fabrication and shipping to the laboratory, and total workflow costs for a single-unit abutment and crown restoration may be reduced by up to 18% with a digital workflow. (3) The benefits of IOS are not to be taken for granted, however. Some studies have found that patients actually preferred conventional impressions as being more comfortable, and that conventional impressions may take less time. (4) Moreover, although accuracy of IOS is typically comparable to conventional impressions in sextant (eg. Single-tooth) scanning, it is not uncommon to discover larger discrepancies in full-arch scanning. (5) For these reasons, it is vital to evaluate and validate accuracy of new-model scanners.

The Dentsply Sirona Primescan was released in the United States on February 4, 2019. (6) The present study evaluated the Primescan, 3Shape TRIOS and TRIOS 3, iTero Element and Element 2 for trueness and precision.

[1] (ReportsnReports, 2017)
[2] (Aragón, Pontes, Bichara, Flores-Mir, & Normando, 2016) (Atieh MA, 2017)
[3] (Joda & Bragger, 2015)
[4] (Aragón, Pontes, Bichara, Flores-Mir, & Normando, 2016)
[5] (Atieh MA, 2017)
[6] (Skramstad, 2019)

LITERATURE REVIEW

Nedelcu and Persson (7) compared scanning of different materials, specifically Telio CAD PMMA, titanium, zirconia, and gypsum dental stone, and found that material sometimes influenced the accuracy of a scanner. They particularly identified Refractive Index, a measure of how light is bent as it transitions from one medium to another, as a factor in scanner results since it affects the light information that a scanner's sensor receives. Based on this concept, Renne, Ludlow, et al (8) fabricated a model with Telio CAD PMMA resin crowns because it has a refractive index similar to that of enamel. Telio CAD has a reported refractive index of 1.49, while that of enamel is 1.63 and dentin 1.54. (9) They scanned the model with different intraoral scanners and an industrial reference scanner and compared the results using computer mapping-overlay software. A similar protocol was also used by Ender, Zimmermann, and Mehl (10) when they tested a conventional impression using PolyVinyl Siloxane poured in Type IV gypsum and scanned with an InEos X5 laboratory scanner, 3Shape TRIOS 3 (Normal and Insane / high speed modes), Carestream CS 3600, Medit i500, iTero Element 2, Cerec Omnicam (Cerec software versions 4.6.1 and 5.0.0), and Primescan. Nedelcu & Persson also found that adding excess titanium dioxide powder as a scanning medium did not have a statistically significant impact on scanning accuracy, but that scanning medium did tend to yield more accurate results.

[7] (Nedelcu & Persson, 2014)
[8] (Renne, et al., 2017)
[9] (Meng, et al., 2009)
[10] (Ender, Zimmermann, & Mehl, 2019)

In accordance with these findings, we used scanning medium on the model for our master scans, which we performed last to avoid residual medium for any of the test scans.

We replicated aspects of the cited protocols by utilizing different materials in our model, particularly Telio CAD to simulate enamel, a reflective CoCr crown, and a PEEK implant scanbody since these are common intraoral scanning challenges. We also used metrology software to compare digital models in much the same way as the other authors. Use of a similar protocol should facilitate comparison with the previously-tested scanners and inclusion in meta-analyses.

The comparisons we made were for the evaluation of scanner accuracy. Accuracy is defined by the International Organization for Standardization (ISO) as being comprised of 'Trueness' and 'Precision'. (11)(12).

Trueness (historically referred to by the more emotionally laden term Bias) is a way of expressing the closeness of a measurement method's results to an accepted reference value. Often, the physical constant being measured is inherently unknowable with perfection, but trueness can be determined by comparing test measurements to a very accurate reference measurement. In this study, we compared test scans to a reference scan from a highly true and precise master scanner (the GOM ATOS Core 135). In cases where many samples are available, Trueness can be described by comparing the Mean of the measurements to the reference value, which his how we report our results.

Precision is a term for variability between repeated measurements. When a measuring instrument or process has high precision, successive measurements are very close together (irrespective of their closeness to the actual thing being measured). In the real world, precision can be affected by many factors, including the operator; the actual equipment used; calibration of the equipment;

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[11] (International Organization for Standardization, 1994)
[12] (Hulley, Cummings, Browner, Grady, & Newman, 2013)

environmental conditions such as temperature, ambient light, intraoral humidity; and time elapsed between measurements. In our study, we are attempting to evaluate differences between equipment used and control the other factors. One operator performed all measurements, using as close to the same scanning protocol as possible on each scan. The scanners were all calibrated before testing, with the exception of the iTero machines because we were not able to identify a user calibration protocol. Ambient light was 'normal' indoor conditions, although this variable could be difficult to control for machines in different locations. Intraoral humidity was not simulated; therefore, all measurements were made at 'unremarkable indoor' humidity conditions. Finally, all measurements on a specific machine were made consecutively in one session. As a measure of variability, precision is usually expressed in terms of the Standard Deviation of measurements—and we follow this method in reporting our results.

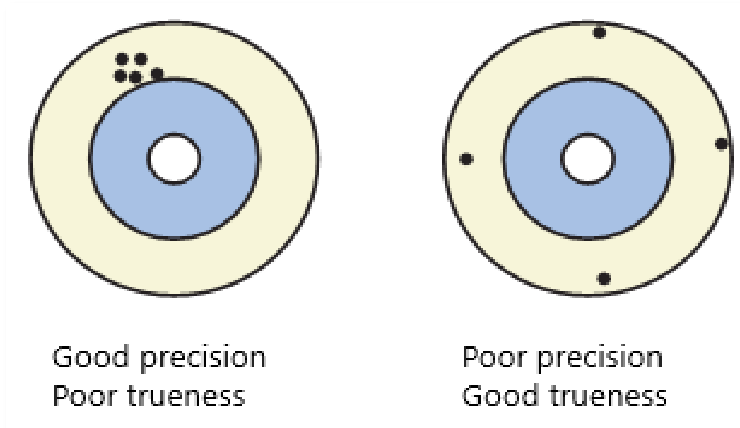

Figure 1: Accuracy is a combination of Trueness and Precision.
Adapted from: Hulley et al., 36

STATEMENT OF PURPOSE

The purpose of this study is to augment the body of literature regarding leading commercially available Intra-Oral Scanners. This will assist clinicians in evaluating the suitability of IOS for clinical use, particularly in full-arch applications where IOS have struggled to provide results comparable to traditional, physical impression methods.

We evaluated the trueness and precision of the following intraoral scanners:

- Dentsply Sirona Primescan
- 3Shape TRIOS
- 3Shape TRIOS 3
- iTero Element
- iTero Element 2

HYPOTHESIS

The null hypothesis is that there are no statistically significant differences in trueness or precision of the tested scanners when compared with the digital model produced by the industrial reference scanner, the GOM ATOS Core 135.

The GOM ATOS Core 135 is a high precision, high trueness bench-top scanner that scans the entire cast simultaneously. It also optionally uses titanium dioxide scanning medium to coat the cast with a uniform, easily scannable material. In contrast, Intra-Oral Scanners must fit into a patient's mouth and therefore can only capture images of a localized part of the dentition. They must stitch these images together to produce a complete digital cast. Moreover, all current IOS eschew scanning medium in favor of patient and operator convenience. This means they must deal with various materials with different reflective properties and refractive indices to produce a unified digital cast. In order to satisfy the null hypothesis, the IOS must overcome these limitations and produce casts with the same accuracy as the ATOS Core 135.

MATERIALS

Intraoral Scanners

- Dentsply Sirona Primescan (5 scanners)
- 3Shape TRIOS (3 scanners)
- 3Shape TRIOS 3 (5 scanners)
- iTero Element (2 scanners)
- iTero Element 2 (3 scanners)

Industrial Scanner

- GOM ATOS Core 135

Reference Model

- Dentoform, Columbia M-PVR-1560 (Maxillary only)
- Type IV Gypsum die stone, Whip Mix Silky-Rock, ISO Type 4
- Milled Telio CAD PMMA crowns (14 ct, teeth 2-15)
- Implant Analog, Straumann Bone Level RC 025.4101
- Scanbody, Straumann CARES RC Mono 025.4915
- Crown, CoCr, produced by Selective Laser Melting (SLM)
- GC Fujicem 2 resin modified glass ionomer cement

Conventional Impression

- Triad TrueTray UDMA sheets
- PVS impression material, Dentsply Aquasil Ultra+ LV REF 170119, Aquasil Ultra Heavy REF 170411
- Impression Post, Straumann RC, PEEK, screw-retained REF 025.4205
- V.P.S. Tray Adhesive, Kerr REF 25777
- GOM Inspect Professional software version 2017 Hotfix 7, Rev. 113517, Build 2018-11-12, including Inspection Kernel GOM v2.0.1

THE SCANNERS

Dentsply Sirona Primescan

The Primescan was released in the United States on February 4, 2019. (13) Dentsply Sirona was the original intraoral scanner company with their CEREC line, and they estimate that 30,000 of their scanners are in use worldwide, producing a digital impression every 4 seconds on average. The Primescan is their latest scanner, and they report that it has high-resolution data processing capacity for 1,000,000 point per second data resolution composing more than 50,000 consolidated images per second. (14) It has a dynamic scanning depth of up to 20 mm, meaning that it can resolve objects 20 mm away from the scanning wand, improving interproximal scanning

Figure 2: Test scanners, Dentsply Sirona Primescan

[13] (Dentsply Sirona, 2019)
[14] (Dentsply Sirona, 2020)

ability. At the time of writing (April 2020), several new studies have been published evaluating the accuracy of the Primescan. (15)(16)(17)(18)(19)(20)

3Shape TRIOS

The 3Shape TRIOS has been available since January 2012, about the same time as Sirona's Omnicam. (21, 22) (Dentsply International Inc. and Sirona Dental Systems Inc. merged in February 2016. (23)) The TRIOS introduced high speed, color, and scanning without titanium dioxide scanning medium.

3Shape TRIOS 3

The 3Shape TRIOS 3 was released at the International Dental Show in Cologne, Germany on March 10, 2015. (24) Besides enhanced speed, added features included a pen grip form factor for the scanner, intraoral camera function, and teeth shade measurement tool. 3Shape touts its compatibility with many different workflows, and the scanners are popular for communicating with independent dental laboratories. Accuracy has been well established in the literature, with 3Shape citing verification by at least 18 independent studies. They claim ideal trueness of 6.9 ± 0.9 μm and precision of 4.5 ± 0.9 μm (25).

iTero Element

Align Technology is responsible for the Invisalign orthodontic system, and their iTero scanner is closely integrated with that system. It was announced in March 2015 at the International Dental Show in Cologne, Germany (same as the TRIOS 3) for release in late 2015. It superseded the prior iTero Scanner

[15] (Schmidt, Klussmann, Wöstmann, & Schlenz, 2020)
[16] (Cao, et al., 2020)
[17] (Reich, Yatmaz, & Raith, 2020)
[18] (Zimmerman, Ender, & Mehl, 2020)
[19] (Passos, Meiga, Brigagão, & Street, 2019)
[20] (Ender, Zimmermann, & Mehl, 2019)
[21] (3Shape A/S, 2012)
[22] (Puri, 2012)
[23] (Endeavor Business Media, LLC, 2016)
[24] (3Shape A/S, 2015)
[25] (3Shape A/S, 2019)

with improved imaging technology for 20x faster scan speed, higher accuracy, and color rendition. (26) The user interface emphasizes simplicity.

iTero Element 2

The iTero Element 2, released in April 2018, was built on the imaging platform of the Element scanner but boasted more robust computing hardware with 2x faster startup and 25% faster scan processing. These upgrades provided improved processing capability in scanning full arches with their large amount of data. (27)

[26] (Acquire Media, 2015)
[27] (Acquire Media, 2018)

METHODS

REFERENCE MODEL

A reference model was constructed in the following manner. A Columbia maxillary dentoform with implant Impression Post (Straumann RC) attached at Universal Numbering System tooth position 1 was impressed using Aquasil PVS impression materials. The impression used a custom tray made from light-cured Triad TruTray UDMA sheets coated with Kerr V.P.S. Tray Adhesive. After the impression was separated from the dentoform, a Straumann Implant Analog (Bone Level RC) was attached to the Impression Post and the cast poured in Silky-Rock Type IV dental stone mixed according to the manufacturer's recommended water to powder ratio. The resulting cast was prepared as for lithium disilicate full-contour crowns according to Rosenstiel's recommendations (28), except for tooth 16, which received preparation for a metal alloy crown. The milled

Figure 3: Stone master model with crown preparations

Figure 4: Master model: Type IV stone, CoCr and Telio CAD crowns, and PEEK scanbody

[28] (Rosenstiel, Land, & Fujimoto, 2001)

PMMA and metal alloy crowns were fabricated and luted to the stone cast teeth using GC Fujicem 2 resin modified glass ionomer cement. A scanbody (Straumann CARES RC Mono) was attached to the implant analog, completing preparation of the reference model.

We used a solid model, rather than directly scanning a dentoform, because the dentoform has many moveable joints between the simulated teeth and the dentoform frame; whereas a stone cast is rigid and therefore less susceptible to change between scans.

The model was designed to present several scanning challenges to the various scanners. First, highly reflective surfaces commonly make it difficult for a scanner to lock onto a surface, so the CoCr crown was included to test this ability and the accuracy of the resulting surface scan data.

Next, crowns 2 – 15 were made from Telio CAD resin to simulate enamel because they have similar refractive indices, as discussed in the Literature Review. (29)

Implant scanbodies can be difficult for the scanners to stitch together due to their unique, non-dentoform shape, and we found that some scanners scanned the scanbody more easily than others.

Finally, the uniform surface of the palate was difficult for all of the scanners. Again, some performed better than others, while the artificial intelligence software of the Primescan refused to scan it at all. This could be seen as a potential advantage, since at least it avoided reporting inaccurate data. Whenever scanning uniform, featureless surfaces, we recommend placing adhesive markers to give the scan software more texture to work with.

TEST SCANS

The reference model was next scanned with representative scanners each of the Dentsply Sirona Primescan, 3Shape TRIOS and TRIOS 3, and iTero Element and Element 2 systems producing sample data digital models. Before scanning, the Primescan, TRIOS, and TRIOS 3 machines were each

[29] (Nedelcu & Persson, 2014)

calibrated according to the manufacturer's instructions. We were not able to calibrate the iTero Element or Element 2 machines because we were not able to identify a manufacturer-recommended procedure for user calibration. All scanner external optics were cleaned to spotless condition before scanning. The models were exported in the format of Standard Tessellation Language (STL), a common digital mesh interchange format. (30) We collected data from multiple machines of each type to enable us to evaluate the repeatability of performance between scanners of a given type, a feature of this study that we typically have not seen in other studies. Our goal was to collect data from 5 scanners of each type, although limited availability of the 3Shape TRIOS, iTero Element, and iTero Element 2 did not allow us to collect that many. Table 1 shows how many scanners of each type we were able to test.

Scanner Type	Number of Scanners	Scans Per Scanner	Total Scans
Dentsply Sirona Primescan	5	5	25
3Shape TRIOS	3	5	15
3Shape TRIOS 3	5	5	25
iTero Element	2	5	10
iTero Element 2	3	5	15

Table 1: Number of scanners and scans of each type

Mennito (31) and others have shown that scan pattern affects scanning results. Although we appreciate that optimal scan pattern can vary by scanner type, we found it difficult to vary the pattern

[30] (Chakravorty, 2019)
[31] (Mennito, et al., 2018)

much when replicating intraoral full arch scanning. For this reason, we chose one ‘reasonable’ scan pattern and attempted to scan as uniformly as possible. Figure 5 shows the pattern we used. We started at tooth 1, passed along the occlusal surfaces around the arch (maintaining the angulation to capture some buccal and lingual surfaces to aid image alignment), turned to the palatal at the location of scanbody 16, passed around the arch capturing the palatal surfaces until reaching tooth 1, then crossed over to the buccal aspect and passed around the arch capturing the buccal surfaces until reaching scanbody 16. We then found it was necessary to fill in missed interproximal surfaces, palate, and facial gingiva as well. We sought to maintain as uniform movements as possible in filling in these areas, although variations in scanners’ ability to lock on to the previously scanned areas, as well as artificial intelligence tendency to delete sections, required significant variation in movements for these last areas.

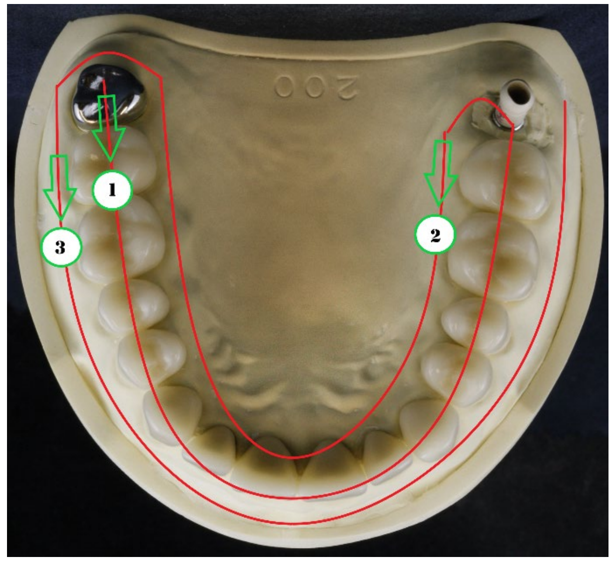

Figure 5: Full arch scan pattern

MASTER SCANS

The reference model was scanned using a validated industrial reference scanner (GOM ATOS Core 135), which has been shown to have maximum repeatability of 3 µm at intraoral sizes. (32) We made 5 scans with the Core 135 to verify the precision of this scanner. We chose the digital model with the fewest apparent defects (for example unscanned interproximal or sulcular regions) for use as the master model for statistical comparison with the other scanners. Since scanning medium was found to remove the influence of refractive index and reflectivity of different materials, and the thickness of the medium was found not to have an adverse effect on accuracy (33), we applied a very thin layer of titanium dioxide powder to the master cast with an airbrush before performing the master scans. To avoid scanning medium affecting the test scans, this was done after all of the test scans. The master scanning procedures were performed professionally by engineers at Capture3D, Inc. (Cornelius, North Carolina, USA).

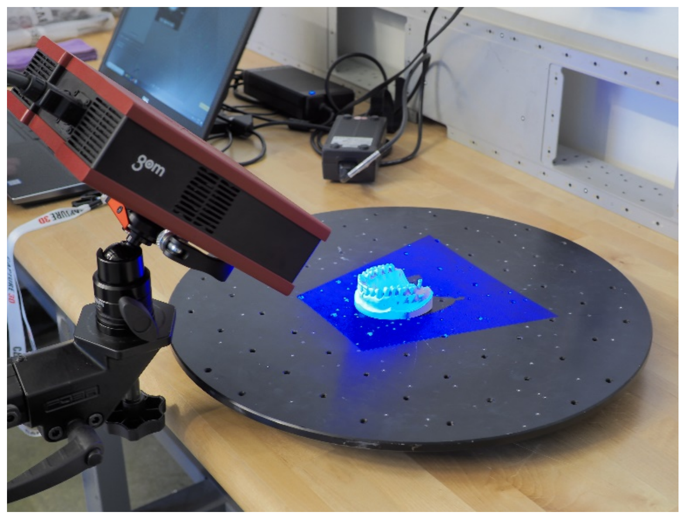

Figure 6: Master scanning was performed with the GOM ATOS Core 135 industrial scanner.

METROLOGY

Each of the digital models was imported into GOM Inspect Professional software for 3 dimensional metrology analysis. The digital test models were compared with the master model by the following procedure. First, the master model is imported into the software and assigned as the Nominal element for comparison. Next, the test models are imported and assigned as Actual elements for

[32] (Dold, et al., 2014)
[33] (Nedelcu & Persson, 2014)

comparison. The two models must then be aligned, where the software overlays the two models for the best mathematical fit. Once the two models are aligned, comparisons can be computed, where the computer measures the difference from the Master model to the Test model at each point on the surface of the model. The computer reports these as a set of statistical parameters, most usefully the Mean (Trueness) and Standard Deviation (Precision). It also depicts the models onscreen with regions color-coded showing the amount of deviation between the models, in micrometers. This visualization also includes a histogram showing the distribution of deviations. (See Figure 7)

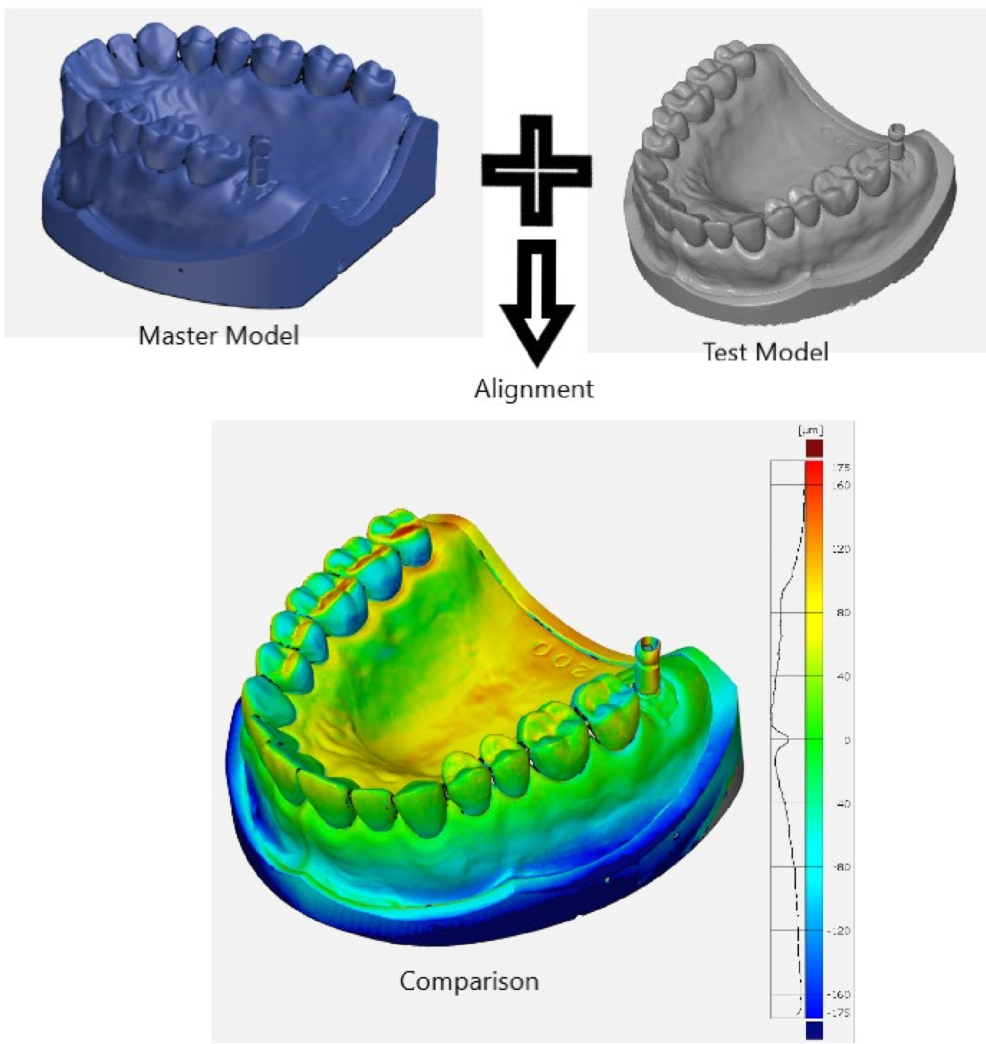

Figure 7: Alignment and comparison for 3D measurements

Metrological comparisons can be done in endless ways. The first point of decision involves the alignment: when the computer aligns the two models, should it calculate the best fit of all parts of the model, or should it favor a critical region, such as the teeth? Since different regions of the master model were made of various materials and gave different scanning results, alignment on each of these material regions makes a large difference in the overall alignment of the models. For the majority of our comparisons, we considered that teeth 2-15 (the Telio CAD crowns simulating dental enamel) were the most important region and therefore set the software to align with the best fit on these teeth.

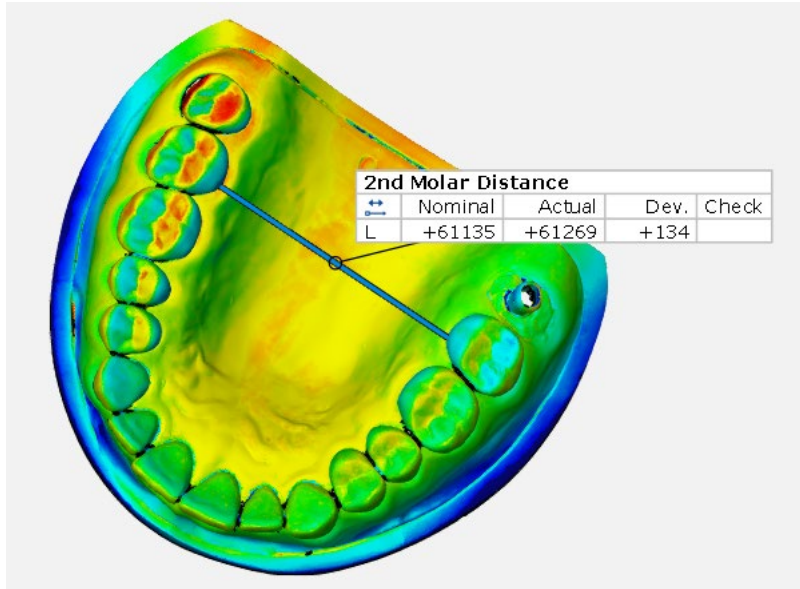

Figure 8: Cross-arch distance comparison.

Nominal: Distance (μm) on the master model
Actual: Distance on the test model
Deviation: Difference between Actual and Nominal

Likewise, an endless array of comparisons can be made. We can compare the entire model or narrow the comparison to a specific region, such as Teeth 2-15 (Telio CAD crowns), Tooth 16 (CoCr crown), Scanbody 1, or the palate or gingiva (Type IV dental stone). We also made comparisons of the full arch, the posterior sextant (teeth 12-15), and the anterior sextant (teeth 6-11). Finally, we measured distance across the arch from the buccal surface of tooth 2 to the buccal surface of tooth 15. (See Figure 8).

STATISTICAL ANALYSIS

Statistical analysis was performed by a statistician. For each outcome, we fit a linear mixed model with a random intercept for scanner and a fixed effect for scanner type. The random intercept for scanner accounted for the correlated scans within a scanner. We then tested for the effect of scanner type. First, we did an overall test of whether any scanner types appeared to be significantly different from each other. If they did, we performed pairwise comparisons between all scanner types and adjusted these pairwise comparisons for multiplicity using a Scheffe correction.

For each statistical model, we used the following parameters:

Null hypothesis: The Mean Distance and Distance Standard Deviation are equal to 0 when the test models produced by a given scanner type are compared to the master reference model. We set the standard for statistical significance as $P < 0.05$.

In all, our analysis included 90 scans, and we ran 10 different statistical models for the five scanner types. In order to narrow these data down to a useful set, we will discuss our results in the context of questions that may be analyzed.

RESULTS

QUESTION 1: WHICH TYPE OF SCANNER HAS THE BEST ACCURACY (PRECISION AND TRUENESS)?

Posterior Sextant Scanning

First we will consider posterior sextant scanning (teeth 12-15). The test models were aligned to the master model with the best mathematical fit for the Telio CAD teeth 2-15; then Mean Deviation (Trueness) and Standard Deviation (Precision) were measured on the posterior sextant.

Trueness

Least Squares Means						
Effect	**Type**	**Estimate**	**Standard Error**	**Alpha**	**Lower**	**Upper**
Type	Element	-13.6000	6.6783	0.05	-26.9129	-0.2871
Type	Element 2	-11.1333	5.4528	0.05	-22.0033	-0.2634
Type	Primescan	-2.2800	4.2237	0.05	-10.6998	6.1398
Type	TRIOS	7.5333	5.4528	0.05	-3.3366	18.4033
Type	TRIOS 3	6.9200	4.2237	0.05	-1.4998	15.3398

Table 2: Estimated Mean Deviation of Scanners from Master (Trueness; Posterior Sextant)
(Closer to 0 μm is better.)

Differences of Least Squares Means														
Effect	**Type**	**Type**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Adjustment**	**Adj P**	**Alpha**	**Lower**	**Upper**	**Adj Lower**	**Adj Upper**
Type	Element	Element 2	-2.4667	8.6216	72	-0.29	0.7756	Scheffe	0.9992	0.05	-19.6536	14.7203	-29.7248	24.7915
Type	Element	Primescan	-11.3200	7.9019	72	-1.43	0.1563	Scheffe	0.7263	0.05	-27.0721	4.4321	-36.3025	13.6625
Type	Element	TRIOS	-21.1333	8.6216	72	-2.45	0.0167	Scheffe	0.2106	0.05	-38.3203	-3.9464	-48.3915	6.1248
Type	Element	TRIOS 3	-20.5200	7.9019	72	-2.60	0.0114	Scheffe	0.1626	0.05	-36.2721	-4.7679	-45.5025	4.4625
Type	Element 2	Primescan	-8.8533	6.8973	72	-1.28	0.2034	Scheffe	0.7995	0.05	-22.6029	4.8962	-30.6599	12.9532
Type	Element 2	TRIOS	-18.6667	7.7114	72	-2.42	0.0180	Scheffe	0.2218	0.05	-34.0391	-3.2942	-43.0471	5.7138
Type	Element 2	TRIOS 3	-18.0533	6.8973	72	-2.62	0.0108	Scheffe	0.1565	0.05	-31.8029	-4.3038	-39.8599	3.7532
Type	Primescan	TRIOS	-9.8133	6.8973	72	-1.42	0.1591	Scheffe	0.7314	0.05	-23.5629	3.9362	-31.6199	11.9932
Type	Primescan	TRIOS 3	-9.2000	5.9733	72	-1.54	0.1279	Scheffe	0.6688	0.05	-21.1075	2.7075	-28.0850	9.6850
Type	TRIOS	TRIOS 3	0.6133	6.8973	72	0.09	[illegible]	Scheffe	1.0000	0.05	[illegible]	[illegible]	[illegible]	[illegible]

Table 3: Pairwise Comparisons of Mean Deviations, Corrected for Multiple Comparisons (Trueness; Posterior Sextant)
(P must be < 0.05 to be considered statistically significantly different; none reached this level.)

Posterior Sextant Scanning (Continued)

Precision

Least Squares Means						
Effect	**Type**	**Estimate**	**Standard Error**	**Alpha**	**Lower**	**Upper**
Type	Element	80.0000	13.5034	0.05	53.0815	106.92
Type	Element 2	79.1333	11.0254	0.05	57.1545	101.11
Type	Primescan	78.4000	8.5403	0.05	61.3753	95.4247
Type	TRIOS	127.60	11.0254	0.05	105.62	149.58
Type	TRIOS 3	84.8000	8.5403	0.05	67.7753	101.82

Table 4: Estimated Standard Deviation of Scanners from Master (Precision; Posterior Sextant)
(Closer to 0 μm is better.)

Differences of Least Squares Means														
Effect	**Type**	**Type**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Adjustment**	**Adj P**	**Alpha**	**Lower**	**Upper**	**Adj Lower**	**Adj Upper**
Type	Element	Element 2	0.8667	17.4328	72	0.05	0.9605	Scheffe	1.0000	0.05	-33.8849	35.6182	-54.2486	55.9820
Type	Element	Primescan	1.6000	15.9774	72	0.10	0.9205	Scheffe	1.0000	0.05	-30.2503	33.4503	-48.9140	52.1140
Type	Element	TRIOS	-47.6000	17.4328	72	-2.73	0.0079	Scheffe	0.1261	0.05	-82.3516	-12.8484	-102.72	7.5153
Type	Element	TRIOS 3	-4.8000	15.9774	72	-0.30	0.7647	Scheffe	0.9990	0.05	-36.6503	27.0503	-55.3140	45.7140
Type	Element 2	Primescan	0.7333	13.9462	72	0.05	0.9582	Scheffe	1.0000	0.05	-27.0679	28.5346	-43.3589	44.8256
Type	Element 2	TRIOS	-48.4667	15.5923	72	-3.11	0.0027	Scheffe	0.0565	0.05	-79.5494	-17.3839	-97.7633	0.8300
Type	Element 2	TRIOS 3	-5.6667	13.9462	72	-0.41	0.6857	Scheffe	0.9967	0.05	-33.4679	22.1346	-49.7589	38.4256
Type	Primescan	TRIOS	-49.2000	13.9462	72	-3.53	0.0007	Scheffe	0.0203	0.05	-77.0013	-21.3987	-93.2923	-5.1077
Type	Primescan	TRIOS 3	-6.4000	12.0778	72	-0.53	0.5978	Scheffe	0.9908	0.05	-30.4766	17.6766	-44.5850	31.7850
Type	TRIOS	TRIOS 3	42.8000	13.9462	72	3.07	0.0030	Scheffe	0.0618	0.05	14.9987	70.6013	-1.2923	86.8923

Table 5: Pairwise Comparisons of Standard Deviations, Corrected for Multiple Comparisons (Precision; Posterior Sextant)
(P must be < 0.05 to be considered statistically significantly different; Yellow highlights)

For the posterior sextant scanning of Telio CAD crowns, we found no statistically significant differences in trueness between all of the scanner types. The Primescan was found to have better precision than the TRIOS.

Anterior Sextant Scanning

Next we will consider anterior sextant scanning (teeth 6-11). The test models were aligned to the master model with the best mathematical fit for the Telio CAD teeth 2-15; then Mean Deviation (Trueness) and Standard Deviation (Precision) were measured on the anterior sextant.

Trueness

Least Squares Means						
Effect	**Type**	**Estimate**	**Standard Error**	**Alpha**	**Lower**	**Upper**
Type	Element	-17.8000	2.5645	0.05	-22.9122	-12.6878
Type	Element 2	-19.2000	2.0939	0.05	-23.3741	-15.0259
Type	Primescan	-12.4000	1.6219	0.05	-15.6332	-9.1668
Type	TRIOS	-6.0000	2.0939	0.05	-10.1741	-1.8259
Type	TRIOS 3	-4.9600	1.6219	0.05	-8.1932	-1.7268

Table 6: Estimated Mean Deviation of Scanners from Master (Trueness; Anterior Sextant)
(Closer to 0 μm is better.)

Differences of Least Squares Means														
Effect	**Type**	**Type**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Adjustment**	**Adj P**	**Alpha**	**Lower**	**Upper**	**Adj Lower**	**Adj Upper**
Type	Element	Element 2	1.4000	3.3107	72	0.42	0.6736	Scheffe	0.9961	0.05	-5.1998	7.9998	-9.0671	11.8671
Type	Element	Primescan	-5.4000	3.0343	72	-1.78	0.0794	Scheffe	0.5343	0.05	-11.4488	0.6488	-14.9932	4.1932
Type	Element	TRIOS	-11.8000	3.3107	72	-3.56	0.0007	Scheffe	0.0184	0.05	-18.3998	-5.2002	-22.2671	-1.3329
Type	Element	TRIOS 3	-12.8400	3.0343	72	-4.23	<.0001	Scheffe	0.0028	0.05	-18.8888	-6.7912	-22.4332	-3.2468
Type	Element 2	Primescan	-6.8000	2.6486	72	-2.57	0.0123	Scheffe	0.1716	0.05	-12.0798	-1.5202	-15.1737	1.5737
Type	Element 2	TRIOS	-13.2000	2.9612	72	-4.46	<.0001	Scheffe	0.0014	0.05	-19.1030	-7.2970	-22.5621	-3.8379
Type	Element 2	TRIOS 3	-14.2400	2.6486	72	-5.38	<.0001	Scheffe	<.0001	0.05	-19.5198	-8.9602	-22.6137	-5.8663
Type	Primescan	TRIOS	-6.4000	2.6486	72	-2.42	0.0182	Scheffe	0.2234	0.05	-11.6798	-1.1202	-14.7737	1.9737
Type	Primescan	TRIOS 3	-7.4400	2.2937	72	-3.24	0.0018	Scheffe	0.0412	0.05	-12.0124	-2.8676	-14.6918	-0.1882
Type	TRIOS	TRIOS 3	-1.0400	2.6486	72	-0.39	0.6957	Scheffe	0.9971	0.05	-6.3198	4.2398	-9.4137	7.3337

Table 7: Pairwise Comparisons of Mean Deviations, Corrected for Multiple Comparisons (Trueness; Anterior Sextant)
(P must be < 0.05 to be considered statistically significantly different; Yellow highlights)

Anterior Sextant Scanning (Continued)

Precision

Effect	Type	Estimate	Standard Error	Alpha	Lower	Upper
Type	Element	70.2000	1.6850	0.05	66.8410	73.5590
Type	Element 2	71.5333	1.3758	0.05	68.7907	74.2760
Type	Primescan	77.3200	1.0657	0.05	75.1956	79.4444
Type	TRIOS	66.5333	1.3758	0.05	63.7907	69.2760
Type	TRIOS 3	63.8400	1.0657	0.05	61.7156	65.9644

Table 8: Estimated Standard Deviation of Scanners from Master (Precision; Anterior Sextant)
(Closer to 0 μm is better.)

Differences of Least Squares Means														
Effect	Type	Type	Estimate	Standard Error	DF	t Value	Pr > |t|	Adjustment	Adj P	Alpha	Lower	Upper	Adj Lower	Adj Upper
Type	Element	Element 2	-1.3333	2.1753	72	-0.61	0.5419	Scheffe	0.9841	0.05	-5.6698	3.0031	-8.2109	5.5442
Type	Element	Primescan	-7.1200	1.9937	72	-3.57	0.0006	Scheffe	0.0181	0.05	-11.0944	-3.1456	-13.4234	-0.8166
Type	Element	TRIOS	3.6667	2.1753	72	1.69	0.0962	Scheffe	0.5876	0.05	-0.6698	8.0031	-3.2109	10.5442
Type	Element	TRIOS 3	6.3600	1.9937	72	3.19	0.0021	Scheffe	0.0468	0.05	2.3856	10.3344	0.05663	12.6634
Type	Element 2	Primescan	-5.7867	1.7403	72	-3.33	0.0014	Scheffe	0.0338	0.05	-9.2558	-2.3175	-11.2887	-0.2846
Type	Element 2	TRIOS	5.0000	1.9457	72	2.57	0.0122	Scheffe	0.1709	0.05	1.1214	8.8786	-1.1515	11.1515
Type	Element 2	TRIOS 3	7.6933	1.7403	72	4.42	<.0001	Scheffe	0.0015	0.05	4.2242	11.1625	2.1913	13.1954
Type	Primescan	TRIOS	10.7867	1.7403	72	6.20	<.0001	Scheffe	<.0001	0.05	7.3175	14.2558	5.2846	16.2887
Type	Primescan	TRIOS 3	13.4800	1.5071	72	8.94	<.0001	Scheffe	<.0001	0.05	10.4756	16.4844	8.7151	18.2449
Type	TRIOS	TRIOS 3	2.6933	1.7403	72	1.55	0.1261	Scheffe	0.6647	0.05	-0.7758	6.1625	-2.8087	8.1954

Table 9: Pairwise Comparisons of Standard Deviations, Corrected for Multiple Comparisons (Precision; Anterior Sextant)
(P must be < 0.05 to be considered statistically significantly different; Yellow highlights)

For the anterior sextant scanning of Telio CAD crowns, we found the following differences in trueness between all of the scanner types: TRIOS 3 > TRIOS > Primescan > Element > Element 2. Statistically significant differences are highlighted in Table 7.

Regarding precision, the TRIOS 3 and TRIOS again scored best, followed by the Element and Element 2, then Primescan. Statistically significant comparisons are highlighted in Table 9.

Cobalt-Chromium Crown Scanning

The next challenge we presented to the scanners was scanning of the highly reflective CoCr crown at position 16. For this analysis the test models were aligned to the master model with the best mathematical fit for the CoCr crown, and Mean Deviation (Trueness) and Standard Deviation (Precision) were measured on the CoCr crown.

Trueness

Least Squares Means						
Effect	**Type**	**Estimate**	**Standard Error**	**Alpha**	**Lower**	**Upper**
Type	Element	4.5000	4.3682	0.05	-4.2079	13.2079
Type	Element 2	1.2000	3.5666	0.05	-5.9100	8.3100
Type	Primescan	-32.8400	2.7627	0.05	-38.3473	-27.3327
Type	TRIOS	-9.3333	3.5666	0.05	-16.4433	-2.2234
Type	TRIOS 3	-5.4800	2.7627	0.05	-10.9873	0.02734

Table 10: Estimated Mean Deviation of Scanners from Master (Trueness; CoCr Crown)
(Closer to 0 μm is better.)

Differences of Least Squares Means														
Effect	**Type**	**Type**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Adjustment**	**Adj P**	**Alpha**	**Lower**	**Upper**	**Adj Lower**	**Adj Upper**
Type	Element	Element 2	3.3000	5.6393	72	0.59	0.5603	Scheffe	0.9866	0.05	-7.9418	14.5418	-14.5293	21.1293
Type	Element	Primescan	37.3400	5.1685	72	7.22	<.0001	Scheffe	<.0001	0.05	27.0367	47.6433	20.9992	53.6808
Type	Element	TRIOS	13.8333	5.6393	72	2.45	0.0166	Scheffe	0.2100	0.05	2.5915	25.0752	-3.9960	31.6626
Type	Element	TRIOS 3	9.9800	5.1685	72	1.93	0.0574	Scheffe	0.4503	0.05	-0.3233	20.2833	-6.3608	26.3208
Type	Element 2	Primescan	34.0400	4.5115	72	7.55	<.0001	Scheffe	<.0001	0.05	25.0465	43.0335	19.7766	48.3034
Type	Element 2	TRIOS	10.5333	5.0440	72	2.09	0.0403	Scheffe	0.3679	0.05	0.4783	20.5883	-5.4137	26.4803
Type	Element 2	TRIOS 3	6.6800	4.5115	72	1.48	0.1431	Scheffe	0.7010	0.05	-2.3135	15.6735	-7.5834	20.9434
Type	Primescan	TRIOS	-23.5067	4.5115	72	-5.21	<.0001	Scheffe	0.0001	0.05	-32.5001	-14.5132	-37.7701	-9.2432
Type	Primescan	TRIOS 3	-27.3600	3.9070	72	-7.00	<.0001	Scheffe	<.0001	0.05	-35.1486	-19.5714	-39.7125	-15.0075
Type	TRIOS	TRIOS 3	-3.8533	4.5115	72	-0.85	0.3959	Scheffe	0.9468	0.05	-12.8468	5.1401	-18.1168	10.4101

Table 11: Pairwise Comparisons of Mean Deviations, Corrected for Multiple Comparisons (Trueness; CoCr Crown)
(P must be < 0.05 to be considered statistically significantly different; Yellow highlights)

CoCr Crown Scanning (Continued)

Precision

Least Squares Means						
Effect	**Type**	**Estimate**	**Standard Error**	**Alpha**	**Lower**	**Upper**
Type	Element	35.9000	8.7885	0.05	18.3804	53.4196
Type	Element 2	40.8000	7.1758	0.05	26.4953	55.1047
Type	Primescan	155.04	5.5583	0.05	143.96	166.12
Type	TRIOS	102.40	7.1758	0.05	88.0953	116.70
Type	TRIOS 3	96.0400	5.5583	0.05	84.9596	107.12

Table 12: Estimated Standard Deviation of Scanners from Master (Precision; CoCr Crown)
(Closer to 0 μm is better.)

Differences of Least Squares Means														
Effect	**Type**	**Type**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Adjustment**	**Adj P**	**Alpha**	**Lower**	**Upper**	**Adj Lower**	**Adj Upper**
Type	Element	Element 2	-4.9000	11.3459	72	-0.43	0.6671	Scheffe	0.9958	0.05	-27.5177	17.7177	-40.7712	30.9712
Type	Element	Primescan	-119.14	10.3987	72	-11.46	<.0001	Scheffe	<.0001	0.05	-139.87	-98.4106	-152.02	-86.2635
Type	Element	TRIOS	-66.5000	11.3459	72	-5.86	<.0001	Scheffe	<.0001	0.05	-89.1177	-43.8823	-102.37	-30.6288
Type	Element	TRIOS 3	-60.1400	10.3987	72	-5.78	<.0001	Scheffe	<.0001	0.05	-80.8694	-39.4106	-93.0165	-27.2635
Type	Element 2	Primescan	-114.24	9.0767	72	-12.59	<.0001	Scheffe	<.0001	0.05	-132.33	-96.1459	-142.94	-85.5431
Type	Element 2	TRIOS	-61.6000	10.1481	72	-6.07	<.0001	Scheffe	<.0001	0.05	-81.8299	-41.3701	-93.6842	-29.5158
Type	Element 2	TRIOS 3	-55.2400	9.0767	72	-6.09	<.0001	Scheffe	<.0001	0.05	-73.3341	-37.1459	-83.9369	-26.5431
Type	Primescan	TRIOS	52.6400	9.0767	72	5.80	<.0001	Scheffe	<.0001	0.05	34.5459	70.7341	23.9431	81.3369
Type	Primescan	TRIOS 3	59.0000	7.8607	72	7.51	<.0001	Scheffe	<.0001	0.05	43.3300	74.6700	34.1477	83.8523
Type	TRIOS	TRIOS 3	6.3600	9.0767	72	0.70	0.4858	Scheffe	0.9739	0.05	-11.7341	24.4541	-22.3369	35.0569

Table 13: Pairwise Comparisons of Standard Deviations, Corrected for Multiple Comparisons (Precision; CoCr Crown)
(P must be < 0.05 to be considered statistically significantly different; Yellow highlights)

For the scanning of a CoCr posterior crown, we found the following differences in trueness between all of the scanner types: Element 2 > Element > TRIOS 3 > TRIOS > Primescan. Statistically significant differences are highlighted in Table 11.

Regarding precision, the Element and Element 2 again scored best, followed by the TRIOS 3 and TRIOS, then Primescan. Statistically significant comparisons are highlighted in Table 13.

QUESTION 2: WHICH TYPE OF SCANNER HAS THE BEST ACCURACY FOR FULL ARCH SCANNING?

Full Arch Scanning

We now consider performance of the scanner models at scanning the full arch, Telio CAD crowns 2-15 (As a reminder, Telio CAD was chosen because its refractive index approximates that of dental enamel and dentin). For this analysis the test models were aligned to the master model with the best mathematical fit for the Telio CAD crowns 2-15, and Mean Deviation (Trueness) and Standard Deviation (Precision) were measured on the crowns 2-15.

Trueness

Least Squares Means									
Effect	Type	Estimate	Standard Error				Alpha	Lower	Upper
Type	Element	-13.8000	3.0399				0.05	-19.8598	-7.7402
Type	Element 2	-12.6000	2.4820				0.05	-17.5478	-7.6522
Type	Primescan	-7.4400	1.9226				0.05	-11.2726	-3.6074
Type	TRIOS	-0.8667	2.4820				0.05	-5.8145	4.0812
Type	TRIOS 3	-0.1200	1.9226				0.05	-3.9526	3.7126

Table 14: Estimated Mean Deviation of Scanners from Master (Trueness; Full Arch 2-15)
(Closer to 0 μm is better.)

Differences of Least Squares Means														
Effect	Type	Type	Estimate	Standard Error	DF	t Value	Pr > |t|	Adjustment	Adj P	Alpha	Lower	Upper	Adj Lower	Adj Upper
Type	Element	Element 2	-1.2000	3.9244	72	-0.31	0.7607	Scheffe	0.9989	0.05	-9.0232	6.6232	-13.6075	11.2075
Type	Element	Primescan	-6.3600	3.5968	72	-1.77	0.0813	Scheffe	0.5408	0.05	-13.5301	0.8101	-17.7316	5.0116
Type	Element	TRIOS	-12.9333	3.9244	72	-3.30	0.0015	Scheffe	0.0364	0.05	-20.7566	-5.1101	-25.3408	-0.5258
Type	Element	TRIOS 3	-13.6800	3.5968	72	-3.80	0.0003	Scheffe	0.0096	0.05	-20.8501	-6.5099	-25.0516	-2.3084
Type	Element 2	Primescan	-5.1600	3.1396	72	-1.64	0.1046	Scheffe	0.6113	0.05	-11.4186	1.0986	-15.0860	4.7660
Type	Element 2	TRIOS	-11.7333	3.5101	72	-3.34	0.0013	Scheffe	0.0324	0.05	-18.7306	-4.7360	-22.8309	-0.6357
Type	Element 2	TRIOS 3	-12.4800	3.1396	72	-3.98	0.0002	Scheffe	0.0059	0.05	-18.7386	-6.2214	-22.4060	-2.5540
Type	Primescan	TRIOS	-6.5733	3.1396	72	-2.09	0.0398	Scheffe	0.3652	0.05	-12.8319	-0.3147	-16.4993	3.3527
Type	Primescan	TRIOS 3	-7.3200	2.7189	72	-2.69	0.0088	Scheffe	0.1359	0.05	-12.7401	-1.8999	-15.9162	1.2762
Type	TRIOS	TRIOS 3	-0.7467	3.1396	72	-0.24	0.8127	Scheffe	0.9996	0.05	-7.0053	5.5119	-10.6727	9.1793

Table 15: Pairwise Comparisons of Mean Deviations, Corrected for Multiple Comparisons (Trueness; Full Arch 2-15)
(P must be < 0.05 to be considered statistically significantly different; Yellow highlights)

Full Arch Scanning (Continued)

Precision

Least Squares Means									
Effect	Type	Estimate	Standard Error				Alpha	Lower	Upper
Type	Element	72.9000	6.6827				0.05	59.5783	86.2217
Type	Element 2	72.4667	5.4564				0.05	61.5896	83.3438
Type	Primescan	73.4800	4.2265				0.05	65.0546	81.9054
Type	TRIOS	92.3333	5.4564				0.05	81.4562	103.21
Type	TRIOS 3	73.0800	4.2265				0.05	64.6546	81.5054

Table 16: Estimated Standard Deviation of Scanners from Master (Precision; Full Arch 2-15)
(Closer to 0 μm is better.)

Differences of Least Squares Means														
Effect	Type	Type	Estimate	Standard Error	DF	t Value	Pr > |t|	Adjustment	Adj P	Alpha	Lower	Upper	Adj Lower	Adj Upper
Type	Element	Element 2	0.4333	8.6273	72	0.05	0.9601	Scheffe	1.0000	0.05	-16.7648	17.6315	-26.8426	27.7093
Type	Element	Primescan	-0.5800	7.9070	72	-0.07	0.9417	Scheffe	1.0000	0.05	-16.3424	15.1824	-25.5788	24.4188
Type	Element	TRIOS	-19.4333	8.6273	72	-2.25	0.0273	Scheffe	0.2903	0.05	-36.6315	-2.2352	-46.7093	7.8426
Type	Element	TRIOS 3	-0.1800	7.9070	72	-0.02	0.9819	Scheffe	1.0000	0.05	-15.9424	15.5824	-25.1788	24.8188
Type	Element 2	Primescan	-1.0133	6.9018	72	-0.15	0.8837	Scheffe	0.9999	0.05	-14.7719	12.7452	-22.8341	20.8074
Type	Element 2	TRIOS	-19.8667	7.7165	72	-2.57	0.0121	Scheffe	0.1694	0.05	-35.2492	-4.4841	-44.2630	4.5297
Type	Element 2	TRIOS 3	-0.6133	6.9018	72	-0.09	0.9294	Scheffe	1.0000	0.05	-14.3719	13.1452	-22.4341	21.2074
Type	Primescan	TRIOS	-18.8533	6.9018	72	-2.73	0.0079	Scheffe	0.1258	0.05	-32.6119	-5.0948	-40.6741	2.9674
Type	Primescan	TRIOS 3	0.4000	5.9772	72	0.07	0.9468	Scheffe	1.0000	0.05	-11.5152	12.3152	-18.4973	19.2973
Type	TRIOS	TRIOS 3	19.2533	6.9018	72	2.79	0.0067	Scheffe	0.1121	0.05	5.4948	33.0119	-2.5674	41.0741

Table 17: Pairwise Comparisons of Standard Deviations, Corrected for Multiple Comparisons (Precision; Full Arch 2-15)
(P must be < 0.05 to be considered statistically significantly different; None reached that level.)

For the scanning of the full arch of Telio CAD crowns representing unprepared enamel teeth, we found the following differences in trueness between all of the scanner types: TRIOS 3 > TRIOS > Primescan > Element 2 > Element. Statistically significant differences are highlighted in Table 11.

Regarding precision, no statistically significant differences were found between the scanners. These data are presented in Table 13.

Cross-Arch Distance

Another measure of full arch accuracy is to measure the cross-arch distance from the buccal surface of crown 2 to the buccal of crown 15. For this analysis the test models were aligned to the master model with the best mathematical fit for the Telio CAD crowns 2-15, and a caliper tool was used to measure the Deviation (Trueness) of the cross-arch distance. The cross-arch distance on the master model was 61.135 mm.

Trueness

Least Squares Means									
Effect	**Type**	**Estimate**	**Standard Error**				**Alpha**	**Lower**	**Upper**
Type	Element	-11.5000	39.8245				0.05	-90.8888	67.8888
Type	Element 2	-8.1333	32.5166				0.05	-72.9540	56.6873
Type	Primescan	89.2400	25.1873				0.05	39.0301	139.45
Type	TRIOS	215.00	32.5166				0.05	150.18	279.82
Type	TRIOS 3	103.44	25.1873				0.05	53.2301	153.65

Table 18: Estimated Mean Deviation of Scanners from Master (Trueness; Cross-Arch Distance)
(Closer to 0 µm is better.)

Differences of Least Squares Means														
Effect	**Type**	**Type**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Adjustment**	**Adj P**	**Alpha**	**Lower**	**Upper**	**Adj Lower**	**Adj Upper**
Type	Element	Element 2	-3.3667	51.4133	72	-0.07	0.9480	Scheffe	1.0000	0.05	-105.86	99.1238	-165.91	159.18
Type	Element	Primescan	-100.74	47.1210	72	-2.14	0.0359	Scheffe	0.3435	0.05	-194.67	-6.8059	-249.72	48.2376
Type	Element	TRIOS	-226.50	51.4133	72	-4.41	<.0001	Scheffe	0.0016	0.05	-328.99	-124.01	-389.05	-63.9522
Type	Element	TRIOS 3	-114.94	47.1210	72	-2.44	0.0172	Scheffe	0.2150	0.05	-208.87	-21.0059	-263.92	34.0376
Type	Element 2	Primescan	-97.3733	41.1306	72	-2.37	0.0206	Scheffe	0.2423	0.05	-179.37	-15.3810	-227.41	32.6649
Type	Element 2	TRIOS	-223.13	45.9854	72	-4.85	<.0001	Scheffe	0.0004	0.05	-314.80	-131.46	-368.52	-77.7461
Type	Element 2	TRIOS 3	-111.57	41.1306	72	-2.71	0.0083	Scheffe	0.1306	0.05	-193.57	-29.5810	-241.61	18.4649
Type	Primescan	TRIOS	-125.76	41.1306	72	-3.06	0.0031	Scheffe	0.0634	0.05	-207.75	-43.7676	-255.80	4.2783
Type	Primescan	TRIOS 3	-14.2000	35.6202	72	-0.40	0.6913	Scheffe	0.9969	0.05	-85.2075	56.8075	-126.82	98.4165
Type	TRIOS	TRIOS 3	111.56	41.1306	72	2.71	0.0084	Scheffe	0.1307	0.05	29.5676	193.55	-18.4783	241.60

Table 19: Pairwise Comparisons of Mean Deviations, Corrected for Multiple Comparisons (Trueness; Cross-Arch Distance)
(P must be < 0.05 to be considered statistically significantly different; Yellow highlights)

For the Cross-Arch Distance when scanning the full arch of Telio CAD crowns representing unprepared enamel teeth, we found the following differences in trueness between all of the scanner types: Element 2 > Element > Primescan > TRIOS 3 > TRIOS. Statistically significant differences are highlighted in Table 19.

QUESTION 3: WHICH TYPE OF SCANNER DEALS BEST WITH SCANNING DIFFERENT MATERIALS?

As discussed previously, optical qualities of different materials can affect scanning performance. For this reason, we constructed a test model composed of Telio CAD resin, CoCr metal, PEEK resin, and Type IV dental stone. We can estimate a scanner's ability to deal with various materials by changing the alignment of the test model and master model, for instance by aligning on the Telio CAD teeth 2-15 and measuring the accuracy of scanning the CoCr crown or PEEK scanbody.

Mixed Materials: CoCr Crown

First we present data on the performance of the scanner models at scanning the CoCr crown 16 when the models were aligned for best fit on the Telio CAD crowns 2-15.

Trueness

Least Squares Means									
Effect	**Type**	**Estimate**	**Standard Error**	**DF**				**Lower**	**Upper**
Type	Element	51.9000	15.1394	72				21.7201	82.0799
Type	Element 2	8.4667	12.3613	72				-16.1752	33.1085
Type	Primescan	-3.9600	9.5750	72				-23.0475	15.1275
Type	TRIOS	4.1333	12.3613	72				-20.5085	28.7752
Type	TRIOS 3	14.6000	9.5750	72				-4.4875	33.6875

Table 20: Est. Mean Deviation of Scanners from Master (Trueness; CoCr 16, Aligned on crowns 2-15) (Closer to 0 μm is better.)

Differences of Least Squares Means														
Effect	**Type**	**Type**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Adjustment**	**Adj P**	**Alpha**	**Lower**	**Upper**	**Adj Lower**	**Adj Upper**
Type	Element	Element 2	43.4333	19.5449	72	2.22	0.0294	Scheffe	0.3039	0.05	4.4712	82.3955	-18.3598	105.23
Type	Element	Primescan	55.8600	17.9132	72	3.12	0.0026	Scheffe	0.0552	0.05	20.1506	91.5694	-0.7744	112.49
Type	Element	TRIOS	47.7667	19.5449	72	2.44	0.0170	Scheffe	0.2133	0.05	8.8045	86.7288	-14.0265	109.56
Type	Element	TRIOS 3	37.3000	17.9132	72	2.08	0.0409	Scheffe	0.3709	0.05	1.5906	73.0094	-19.3344	93.9344
Type	Element 2	Primescan	12.4267	15.6360	72	0.79	0.4294	Scheffe	0.9588	0.05	-18.7430	43.5964	-37.0079	61.8612
Type	Element 2	TRIOS	4.3333	17.4815	72	0.25	0.8049	Scheffe	0.9995	0.05	-30.5155	39.1821	-50.9362	59.6028
Type	Element 2	TRIOS 3	-6.1333	15.6360	72	-0.39	0.6960	Scheffe	0.9971	0.05	-37.3030	25.0364	-55.5679	43.3012
Type	Primescan	TRIOS	-8.0933	15.6360	72	-0.52	0.6063	Scheffe	0.9916	0.05	-39.2630	23.0764	-57.5279	41.3412
Type	Primescan	TRIOS 3	-18.5600	13.5411	72	-1.37	0.1747	Scheffe	0.7578	0.05	-45.5538	8.4338	-61.3716	24.2516
Type	TRIOS	TRIOS 3	-10.4667	15.6360	72	-0.67	0.5054	Scheffe	0.9779	0.05	-41.6364	20.7030	-59.9012	38.9679

Table 21: Pairwise Comparisons of Mean Deviations, Corrected (Trueness; CoCr 16, Aligned on 2-15) (P must be < 0.05 to be considered statistically significantly different; None reached this threshold, although the Element-Primescan comparison came very close—Yellow highlight)

Mixed Materials: CoCr Crown (Continued)

Precision

Least Squares Means									
Effect	**Type**	**Estimate**	**Standard Error**				**Alpha**	**Lower**	**Upper**
Type	Element	73.7000	27.2726				0.05	19.3331	128.07
Type	Element 2	87.7333	22.2680				0.05	43.3430	132.12
Type	Primescan	181.28	17.2487				0.05	146.90	215.66
Type	TRIOS	208.00	22.2680				0.05	163.61	252.39
Type	TRIOS 3	132.24	17.2487				0.05	97.8554	166.62

Table 22: Estimated Standard Deviation of Scanners from Master (Precision; CoCr 16, Aligned on crowns 2-15)
(Closer to 0 μm is better.)

Differences of Least Squares Means														
Effect	**Type**	**Type**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Adjustment**	**Adj P**	**Alpha**	**Lower**	**Upper**	**Adj Lower**	**Adj Upper**
Type	Element	Element 2	-14.0333	35.2087	72	-0.40	0.6914	Scheffe	0.9969	0.05	-84.2206	56.1540	-125.35	97.2823
Type	Element	Primescan	-107.58	32.2693	72	-3.33	0.0014	Scheffe	0.0331	0.05	-171.91	-43.2523	-209.60	-5.5575
Type	Element	TRIOS	-134.30	35.2087	72	-3.81	0.0003	Scheffe	0.0093	0.05	-204.49	-64.1127	-245.62	-22.9843
Type	Element	TRIOS 3	-58.5400	32.2693	72	-1.81	0.0738	Scheffe	0.5149	0.05	-122.87	5.7877	-160.56	43.4825
Type	Element 2	Primescan	-93.5467	28.1670	72	-3.32	0.0014	Scheffe	0.0342	0.05	-149.70	-37.3968	-182.60	-4.4941
Type	Element 2	TRIOS	-120.27	31.4916	72	-3.82	0.0003	Scheffe	0.0092	0.05	-183.04	-57.4892	-219.83	-20.7029
Type	Element 2	TRIOS 3	-44.5067	28.1670	72	-1.58	0.1185	Scheffe	0.6468	0.05	-100.66	11.6432	-133.56	44.5459
Type	Primescan	TRIOS	-26.7200	28.1670	72	-0.95	0.3460	Scheffe	0.9236	0.05	-82.8698	29.4298	-115.77	62.3325
Type	Primescan	TRIOS 3	49.0400	24.3933	72	2.01	0.0481	Scheffe	0.4079	0.05	0.4128	97.6672	-28.0818	126.16
Type	TRIOS	TRIOS 3	75.7600	28.1670	72	2.69	0.0089	Scheffe	0.1365	0.05	19.6102	131.91	-13.2925	164.81

Table 23: Pairwise Comparisons of Standard Deviations, Corrected for Multiple Comparisons (Precision; CoCr 16, Aligned on crowns 2-15)
(P must be < 0.05 to be considered statistically significantly different; Yellow highlights)

For the mixed-material scanning of the CoCr crown 16 when aligned on the Telio CAD teeth 2-15, we found the following differences in trueness between the scanner types: Primescan > TRIOS > Element 2 > TRIOS 3 > Element. Statistically significant differences are highlighted in Table 21.

Regarding precision, the Element and Element 2 scored best, followed by the TRIOS 3, Primescan, and TRIOS. Statistically significant comparisons are highlighted in Table 23.

Mixed Materials: PEEK Scanbody

Finally we present data on the performance of the scanner models at scanning the PEEK Scanbody 1 when the models were aligned for best fit on the Telio CAD crowns 2-15.

Trueness

Least Squares Means									
Effect	**Type**	**Estimate**	**Standard Error**				**Alpha**	**Lower**	**Upper**
Type	Element	31.4000	4.2759				0.05	22.8761	39.9239
Type	Element 2	18.1333	3.4913				0.05	11.1736	25.0931
Type	Primescan	12.2800	2.7043				0.05	6.8890	17.6710
Type	TRIOS	10.2667	3.4913				0.05	3.3069	17.2264
Type	TRIOS 3	8.0400	2.7043				0.05	2.6490	13.4310

Table 24: Est. Mean Deviation of Scanners from Master (Trueness; PEEK Scanbody 1, Aligned on crowns 2-15)
(Closer to 0 μm is better.)

Differences of Least Squares Means														
Effect	**Type**	**Type**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Adjustment**	**Adj P**	**Alpha**	**Lower**	**Upper**	**Adj Lower**	**Adj Upper**
Type	Element	Element 2	13.2667	5.5202	72	2.40	0.0188	Scheffe	0.2284	0.05	2.2623	24.2710	-4.1860	30.7194
Type	Element	Primescan	19.1200	5.0594	72	3.78	0.0003	Scheffe	0.0103	0.05	9.0343	29.2057	3.1243	35.1157
Type	Element	TRIOS	21.1333	5.5202	72	3.83	0.0003	Scheffe	0.0090	0.05	10.1290	32.1377	3.6806	38.5860
Type	Element	TRIOS 3	23.3600	5.0594	72	4.62	<.0001	Scheffe	0.0008	0.05	13.2743	33.4457	7.3643	39.3557
Type	Element 2	Primescan	5.8533	4.4162	72	1.33	0.1892	Scheffe	0.7799	0.05	-2.9502	14.6568	-8.1088	19.8155
Type	Element 2	TRIOS	7.8667	4.9374	72	1.59	0.1155	Scheffe	0.6394	0.05	-1.9759	17.7093	-7.7435	23.4768
Type	Element 2	TRIOS 3	10.0933	4.4162	72	2.29	0.0252	Scheffe	0.2760	0.05	1.2898	18.8968	-3.8688	24.0555
Type	Primescan	TRIOS	2.0133	4.4162	72	0.46	0.6498	Scheffe	0.9948	0.05	-6.7902	10.8168	-11.9488	15.9755
Type	Primescan	TRIOS 3	4.2400	3.8245	72	1.11	0.2713	Scheffe	0.8722	0.05	-3.3840	11.8640	-7.8516	16.3316
Type	TRIOS	TRIOS 3	2.2267	4.4162	72	0.50	0.6157	Scheffe	0.9924	0.05	-6.5768	11.0302	-11.7355	16.1888

Table 25: Pairwise Comparisons of Mean Deviations, Corrected (Trueness; PEEK Scanbody 1, Aligned on 2-15)
(P must be < 0.05 to be considered statistically significantly different; Yellow highlights)

Mixed Materials: PEEK Scanbody (Continued)

Precision

Solution for Fixed Effects						
Effect	**Type**	**Estimate**	**Standard Error**			
Intercept		64.4800	6.9918			
Type	Element	-8.5800	13.0804			
Type	Element 2	-18.0800	11.4175			
Type	Primescan	-6.4000	9.8879			
Type	TRIOS	-1.6133	11.4175			
Type	TRIOS 3	0	.			

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Type	4	72	0.71	0.5909

Table 26: Linear mixed model for distance standard deviation with fixed effect for scanner type (Precision; PEEK Scanbody 1, Aligned on crowns 2-15).
(Closer to 0 μm is better. Note that P > 0.05, indicating no statistically significant differences.)

Least Squares Means									
Effect	**Type**	**Estimate**	**Standard Error**				**Alpha**	**Lower**	**Upper**
Type	Element	55.9000	11.0550				0.05	33.8623	77.9377
Type	Element 2	46.4000	9.0264				0.05	28.4063	64.3937
Type	Primescan	58.0800	6.9918				0.05	44.1421	72.0179
Type	TRIOS	62.8667	9.0264				0.05	44.8729	80.8604
Type	TRIOS 3	64.4800	6.9918				0.05	50.5421	78.4179

Table 27: Estimated Standard Deviation of Scanners from Master (Precision; PEEK Scanbody 1, Aligned on crowns 2-15)
(Estimate closer to 0 μm is better. Note that all 95% confidence intervals overlap, indicating no statistically significant differences.)

For the mixed-material scanning of the PEEK scanbody 1 when aligned on the Telio CAD teeth 2-15, we found the following differences in trueness between the scanner types: TRIOS 3 > TRIOS > Primescan > Element 2 > Element. Statistically significant differences are highlighted in Table 25.

Regarding precision, no statistically significant differences were found between the scanners. These data are presented in Tables 26 and 27.

		Range (abs. μm)	Element	Element 2	Primescan	TRIOS	TRIOS 3
Posterior Sextant	Trueness	2.28 - 13.6	-13.6	-11.13	-2.28	7.53	6.92
	Precision	78.4 - 127.6	80	79.13	78.4	127.6	84.8
Anterior Sextant	Trueness	4.96 - 19.2	-17.8	-19.2	-12.4	-6	-4.96
	Precision	63.84 - 77.32	70.2	71.53	77.32	66.53	63.84
CoCr Crown	Trueness	1.2 - 32.84	4.5	1.2	-32.84	-9.33	-5.48
	Precision	35.9 - 155.04	35.9	40.8	155.04	102.4	96.04
Full Arch	Trueness	0.12 - 13.8	-13.8	-12.6	-7.44	-0.87	-0.12
	Precision	72.47 - 92.33	72.9	72.47	73.48	92.33	73.08
Cross-Arch	Trueness	8.13 - 215	-11.5	-8.13	89.24	215	103.44
CoCr (Mixed)	Trueness	3.96 - 51.9	51.9*	8.47	-3.96*	4.13	14.6
	Precision	73.7 - 208	73.7	87.73	181.28	208	132.24
PEEK (Mixed)	Trueness	8.04 - 31.4	31.4	18.13	12.28	10.27	8.04
	Precision	46.4 - 64.48	55.9	46.4	58.08	62.87	64.48

Table 28: Summary of Results
Colors indicate rank but not size of difference. Best = Green, light green, yellow, orange, red = Worst
Colors represent statistically significant differences (P < 0.05). White cells represent not statistically significant difference.
*P = 0.0552

DISCUSSION

To assist the reader in differentiating the scanner types, we have provided Table 28 as a summary of the data. The colors represent rankings where statistically significant differences were observed; if a scanner was not involved in a statistically significant difference, then the cell was left white. Note that we included values in the CoCr (Mixed) test for Trueness that did not quite meet the $P<0.05$ threshold for significance, since P was in fact 0.0552.

An important consideration when interpreting the data is the scale of measurements being made, as well as the range of values differentiating one scanner from another. We measured differences on the scale of 0 to 215 microns, and it should be remembered that average sized bacteria, such as Escherichia coli, are about 0.5 μm in diameter by 2 μm long. (34) Therefore the differentiating sizes in this study are not many lengths of an average sized bacterium.

This is particularly true for localized scanning, especially in the posterior region where the mean deviation from the master scanner only ranged from 2.28 – 13.6 μm. This indicates excellent trueness for all scanner types in this type of scan. On the other hand, we should not forget about precision. Here values are reported as standard deviations—the reader is reminded that 32% of point measurements returned by the scanner will be *outside* the range of 1 standard deviation. In the test for posterior sextant scanning, the TRIOS registered a standard deviation of 127.6 μm, which could give cause for concern that so many measurements strayed outside of that range. More statistically significant differences between scanners' accuracy were seen in the Anterior Sextant, where the differing

[34] (Encyclopædia Britannica, 2020)

geometry of the teeth may have affected the results. In addition, the nature of full-arch scanning requires that the orientation of the scanner handpiece be reversed in the middle of the anterior sextant, and this may help account for scanning variability. (35)

At this time most people recognize that intraoral scanners seem to be generally 'good enough' for clinical use in sextant scanning. For this reason, the current study also evaluated full arch scanning accuracy. Here we still found good results, with full arch (Telio CAD crowns 2-15) trueness ranging from 0.12 – 13.8 μm mean deviation. Precision for this scan region ranged from a standard deviation of 72.47 – 92.33 μm for each of the tested scanner models. The scanners' mean deviation from the accepted standard cross arch distance of 61,135 μm was 8.13 μm for the iTero Element 2 to 215 μm for the 3Shape TRIOS systems we tested. The TRIOS is an older system, and based on this result we might think twice before using it for a full arch application. However, the newer TRIOS 3 (and Primescan) did not show a statistically significant difference from the Element 2.

The final consideration we examined was scanning of different materials. In this regard, the older Element appeared to have comparatively reduced trueness, and the older TRIOS had reduced precision; whereas the newer TRIOS 3, Element 2, and Primescan systems faired generally better (Although the Primescan seemed to struggle somewhat with precision on the mirror-like CoCr crowns).

[35] (Mennito, et al., 2018)

CONCLUSION

For full-arch scanning, the TRIOS 3, TRIOS, and Primescan showed the best trueness and precision, while the Element 2, Element, TRIOS 3, and Primescan had the best cross-arch trueness. Only the TRIOS returned results that may be considered clinically problematic for full-arch application.

In scanning the posterior sextant, few differences were seen between all of the scanner types except that the TRIOS units we studied had poorer precision.

In scanning the anterior sextant, the TRIOS and TRIOS 3 exhibited statistically superior trueness and precision.

For highly reflective surfaces such as a posterior CoCr crown, the Element and Element 2 performed best while the Primescan had more difficulty and higher standard deviations for precision.

In scanning mixed materials, the TRIOS 3 and Element 2 appeared to be the most accurate.

All scanners tended to return Mean Deviations within the acceptable range for clinical use; however, the reader is reminded that standard deviation from the mean is also an important parameter in scanning. Since 32% of point measurements returned by the scanner will be outside the range of 1 standard deviation, attention should be paid to the *precision* of scanners, and not just the *trueness*. Since scanner standard deviations commonly ranged to more than 100 μm, we felt that some scanners had precision that could cause a practitioner to consider for which applications it may be more or less appropriate.

HUMAN SUBJECTS

Human Subjects

No human subjects were involved in this study. Institutional Review Board (IRB) approval was not required.

VERTEBRATE ANIMALS

No animals were involved in this study. No Laboratory Animal Protocol was required.

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