THE USE OF SURFACE SCANNERS FOR DIGITAL DATA ACQUISITION.

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SUMMARY

THE DIGITIZATION OF THE DENTAL PROFESSION has brought profound change to the possibilities for today's clinicians. Nearly everything we do in the modern dental practice relies on some form of digital technology, from simple restorative cases to complex surgical cases, including the use of implants, orthodontics, and facially-driven smile design. The use of digital workflows and manufacturing methods is quickly eliminating the common errors and issues encountered when using traditional approaches. The critical linchpin for all of this is acquiring good data to work with through digital scanning. The purpose of this article is to provide an overview of how surface scanning technologies work, how they are evaluated, and how they compare to analog methods with respect to accuracy and potential utilization.

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INTRODUCTION

SIGNIFICANT ADVANCEMENTS IN PROVIDING PATIENTS WITH PREDICTABLE, cost effective solutions have been made thanks to the introduction of digital technologies. For example, production errors that commonly impact prosthetics fabricated by conventional methods are nearly eliminated by utilizing digital workflows. Errors such as impression material distortion, casting and investment errors, and partial denture framework warpage can be eliminated using digital techniques (Ragain et al. 2000; Schaefer et al. 2012). Other issues like plaster expansion, cross arch mounting errors, polymerization shrinkage, bite registration transfers, and wax and gypsum model breakage are virtually a thing of the past (Ragain et al. 2000; Schaefer et al. 2012). Starting these processes digital, i.e. with a digital scan, further enhances the outcome. Transfer of impressions to dental laboratories traditionally involves shipments in the back of trucks or planes for long distances and it is possible for models and impressions to be lost, broken or distorted (Alkurt et al. 2016). Utilizing digital impressions allows for a near instantaneous transferal of the impression to the laboratory using safe and compliant networks. In the case of orthodontics, a digital revolution is occurring because physical models no longer need to be stored for half a decade in expensive rooms, as everything is stored safely in the cloud, freeing up more space for patient treatment (Martin et al. 2015)

The use of an intra-oral scanner (IOS) is the point of "plug and play" connectivity for a practitioner to the new digital reality. This is a welcome change for patients compared to traditional physical impressions, according to several studies (Gjelvold et al. 2016; Haddadi et al. 2018a; Wismeijer et al. 2014). Similarly, clinicians prefer working with intraoral scanners (Lee and Gallucci 2013). This may be due to the dramatic decrease in clinical working time and remake rate when utilizing digital workflows (Grünheid et al. 2014; Joda and Brägger 2016; Yuzbasioglu et al. 2014). Despite the many advantages of digital workflows and the obvious preference for using an IOS instead of a physical impression, many clinicians remain reluctant to incorporate digital impressions into their practice. In the United States, only around 26% of dentists have adopted digital impression technology, while many other parts of the world have lower adoption rates (Leeson 2020). Some of the reasons for this lack of adoption are reasonably intuitive; many clinicians are comfortable with the traditional impressions they learned in school, have a lack of training on implementing digital technologies in their clinical practices, and are faced with an ever-increasing number of IOS to choose from that require a substantial upfront investment when compared to a box of impression trays and material (Stevens 2020).

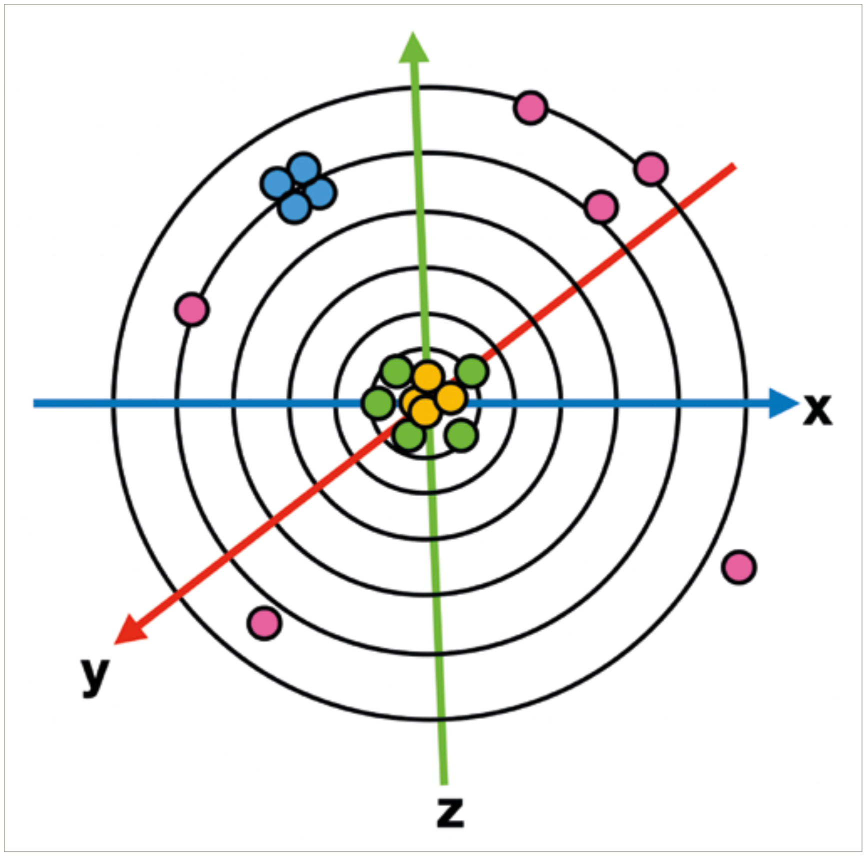

Figure 1.
Four different scenarios. Blue is precise but not true, Pink is not true or precise, Green is true but not precise, and orange is both precise and true.

UNDERSTANDING IOS SCANNER FUNCTION AND ACCURACY

WHEN DISCUSSING SCANNER ACCURACY, whether an IOS or other type of surface scanner, it is important to understand that accuracy, as defined by the International Organization for Standardization, consists of both trueness and precision (International Organization for Standardization 1994). Trueness is defined as the amount a scanned test object deviates from reality (reference standard model). A scanner with higher trueness renders a 3-dimensional (3D) object that more closely matches the original object. Precision represents the repeatability of measurements. A scanner with higher precision delivers more consistent results with repeated scans (Figure 1). Trueness and precision are related but not interdependent. For example, a scanner can be very precise but exhibit poor trueness; in this case it consistently scans an object with a similarly sized deviation each time.

IOS accuracy is dependent on the substrate being scanned. The refraction index, reflectivity, and translucency of what is being scanned changes the amount of light received by an IOS sensor, which can affect the quality of 3D data captured (Bocklet, Renne, Mennito et al. 2019; Dutton, Ludlow, Mennito et al. 2020). As a pattern of light is projected from the scanner onto a surface, the light reflected back into the sensor is used to calculate the location of all data points of interest (POI). If a particular substrate absorbs more light, this may impact the accuracy. The different tissues of the teeth and dental materials have different optical properties. Li and colleagues found that scanners were less accurate when scanning more translucent substrates (Li et al. 2017). This has been confirmed by another research group, which found that substrates scanned have a profound impact on both trueness and precision for several intraoral scanners with materials like thin enamel, translucent composite and ceramics producing less accurate scans, while opaque materials like stone and dentin produce truer scans (Dutton, Ludlow, Mennito et al. 2020). This may be why one sees so much variability in the literature, as one study may use a stone model, while another study uses a cast metal model, and yet another other study may use a typodont or ceramic model. In this instance very different results can be obtained using the same scanner due to the difference in the refractive index of the models. To address this variable, fresh human cadaver study designs have been conducted, which may represent the most realistic substrates for testing IOS accuracy (Bocklet, Renne, Mennito et al. 2019; Mennito, Evans, Nash et al. 2019).

Lighting conditions can also have a major impact on the trueness and precision of scanners. Research lighting conditions vary and are not standardized between studies. Some researchers may use a dark room, some use fluorescent lighting, some use incandescent and others may use light emitting diodes. While some scanners perform the best in complete darkness, other scanners perform best with introduced light (Revilla-León et al. 2020b; Revilla-León et al. 2020d; Wesemann et al. 2020).

The experience of the clinician(s) conducting the research and the scan pattern(s) used are also factors that can influence study outcomes (Resende, Barbosa, Moura et al. 2020). It would be unfair for a researcher to have 10 years of experience with scanner “x”, and then compare it to scanner “y” which they have never used. Unfortunately, this is very common in the research world. In order to address this, several studies have made sure to calibrate clinicians or to use experienced clinicians for each scanner type (Bocklet, Renne, Mennito et al. 2019; Dutton, Ludlow, Mennito et al. 2020; Mennito, Evans, Nash et al. 2019; Vág, Nagy, Bocklet et al. 2020). Scan pattern plays a critical role in the trueness and precision of some scanners especially when scanning complete arches and, therefore, this must be paid attention to in study design (Latham et al. 2020; Mennito et al. 2018). When conducting research, it is important to understand and be familiar with not only the scanner, but the manufacturer recommended scan pattern.

Another variable that is extremely important when evaluating research regarding IOS is the method used to create the reference standard model. The reference standard model is a digital model of an object that is dimensionally as close to reality as possible. This is critical, as it is the model to which all other scans are compared against. Unfortunately, many study designs rely on outdated laboratory scanners to create reference standard models. This is not ideal as many laboratory scanners create 3D objects with profound errors, and therefore the comparisons made using these models are not relevant (Emir and Ayyildiz 2019). Rather than using a dental laboratory scanner, it is recommended to use an industrial scanner, such as the ATOS. The ATOS is a non-contact structured blue-light scanner that works by using multiple cameras that record the projection of stripes on an object being measured with high precision. According to the manufacturer, whose accuracy claims have been verified by several third-party researchers (Dold, Bone, Flohr et al. 2014; Mendricky 2016), for jaw-sized scans this scanner has a trueness of 3 µm and a precision of 2 µm.

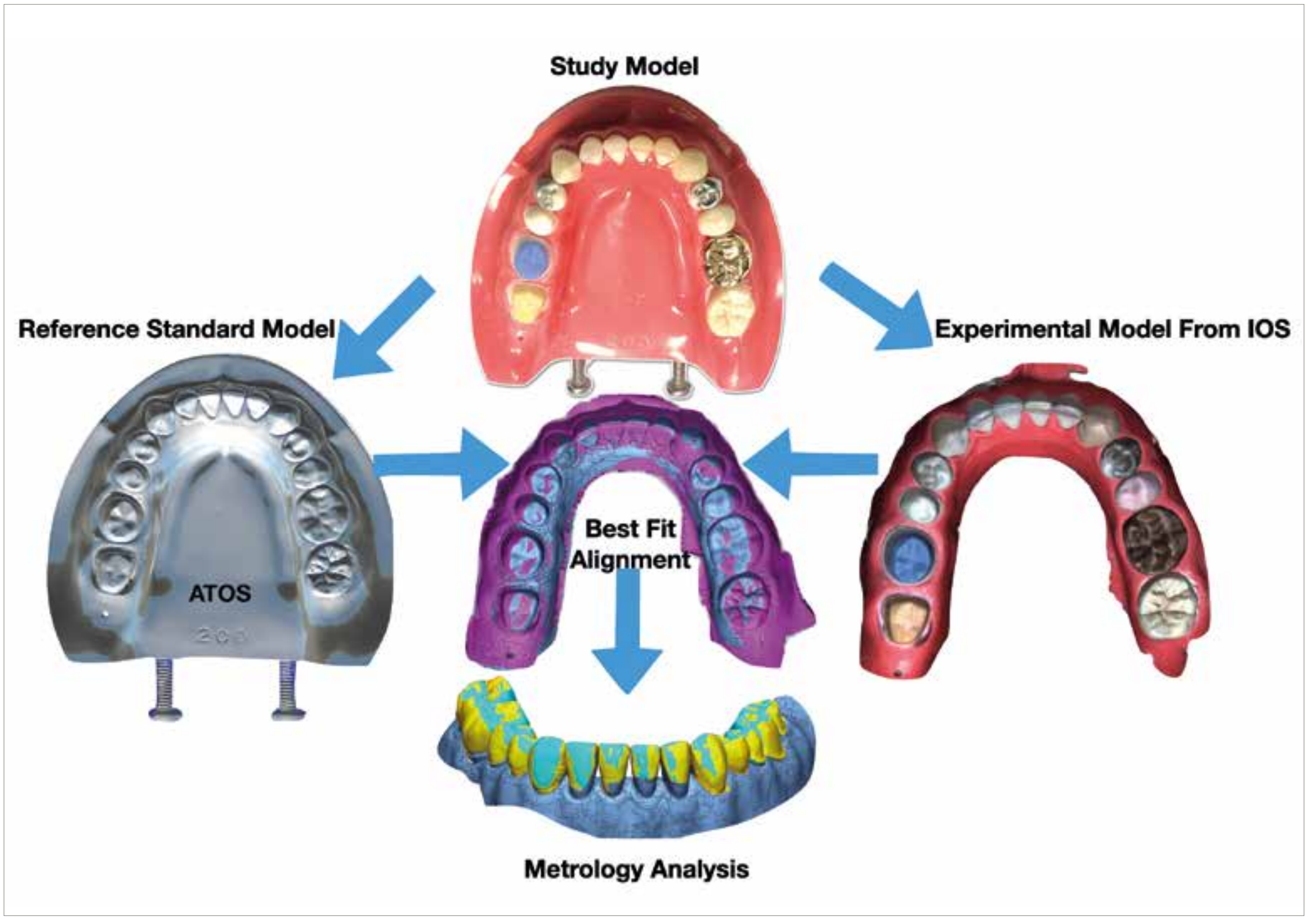

Figure 2.
Classical metrology workflow where a reference standard model is generated from a study model using an industrial scanner. An IOS is used to generate a study model. Software will use best fit alignment to combine the two and then generate a color-coded map of deviations.

The methodology used to evaluate the study models and compare them to the reference standard model is also of importance in research. The most common method for trueness testing of IOS systems is the superimposition of whole scans onto the reference standard file (Figure 2) using iterative best-fit algorithms without considering the scanning point of origin, as developed by Besl and McKay (Besl and McKay 1992) (Figure 2). The problem with iterative best-fit algorithms is that the two models are aligned as much as they can be, independent of the fact that in most cases, these two pixels are not identical in an anatomical or true position. Therefore, deviations calculated in metrology software based on this alignment results in an artificially low average deviation, i.e. making the data more accurate than it really is (Vág, Nagy, Simon et al. 2019).

Lastly, scanner software is also dynamic, with updates occurring often. These updates can dramatically impact the accuracy of the scanners. The very same scanner can nearly double in accuracy with nothing more than a software update (Haddadi et al. 2018b). In summary, operator experience, scan pattern, lighting conditions, substrates being scanned, software version, reference standard model quality and 3D alignment measurement techniques may all impact the trueness and precision of an IOS and how they are evaluated.

A REVIEW OF CURRENT INTRAORAL, LABORATORY, AND FACIAL SCANNER CAPABILITIES

IOS: quadrants and sextants

It has been clear for a number of years that even outdated intraoral scanners have incredible trueness and precision when scanning single tooth, sextant and even quadrants (Lee et al. 2017; Mennito et al. 2018; Renne, Ludlow, Fryml et al. 2017). For example, the CEREC Bluecam (Dentsply Sirona) had reported single tooth trueness of 7.5 ±1.8 µm (Lee et al. 2017), making it one of the most accurate single tooth scanners even when compared to newer scanners today (Bocklet, Renne, Mennito, Evans, Nash et al. 2019; Dutton, Ludlow, Mennito et al. 2020; Mennito et al. 2018; Mennito, Evans, Nash et al. 2019). However, once larger segments were scanned, such as a sextant, the trueness drops to over 50 µm, and for complete arch the trueness plummets to over 150 µm of error (Renne, Ludlow, Fryml et al. 2017). Interestingly, when scanning these smaller areas, scan pattern does not seem to have an impact on accuracy for most scanners on the market (Mennito et al. 2018). A scan pattern study by Mennito and colleagues (Mennito et al. 2018) is of particular interest because their reference standard model was composed of TelioCAD (Ivoclar Vivadent AG). This material is an artificial tooth substance with a refractive index of 1.49, which is close to that of enamel (1.63) and dentin (1.54) (Meng, Yao, Yao et al. 2009). Their study showed that scan pattern did not impact quadrant scan accuracy. More recently, the next generation of rotational based scanners have shown similar accuracy for single tooth areas, with scanner accuracy as low as 19 µm (Zimmerman et al. 2020).

McCracken et al. surveyed 1,777 dentists as to what their preferred impression technique was for single unit crowns; 77% used PVS, 12% used polyether, and only 9% used optical/digital impressions (McCracken, Louis, Litaker et al. 2018). They found that the majority of physical impressions were sextant dual arch impressions made with plastic trays. This type of impression is one of the least accurate impression techniques, with flexure of the plastic tray leading to distortion of the impression, typically causing it to be wide buccal-lingual and short mesial-distal (Santayana de Lima et al. 2014). One study found that when impression material was used in a plastic dual arch tray, gypsum dies were nearly 30 µm smaller in the mesial-distal dimension compared with other techniques (Ceyhan et al. 2003). Therefore, compared to the most common analog techniques for smaller segments, digital impressions are equal to or better than conventional impressions (CI), an assertion that is well supported by clinical outcomes data (Ahlholm et al. 2018; Chochlidakis et al. 2016; Tsirogiannis et al. 2016). Although little to no evidence in the literature has evaluated the accuracy of IOS systems in difficult clinical scenarios such as very deep preparations or areas with contamination. In contrast to the last generation of IOS scanners that struggled to scan in deep areas clinically, most modern scanners have profound depth of fields ranging from 15- 20 mm and are able to scan into deep areas. Furthermore it is the authors opinion that the better color renderings on new IOS systems are of help with margin detection in deep areas. Looking at the literature we can draw some conclusions from marginal fit studies. It has been shown that direct digitization with IOS leads to better fitting crowns than indirect digitization techniques (Freire et al. 2020). In a recent meta-analysis Hasanzade et al concluded that complete digital worlkflows utilizing IOS lead to restorations with comparable or better adaptation than conventional workflows (Hasanzade et. al 2020).

IOS: dentate complete arches

When trueness and precision of models generated from intraoral scanners are evaluated and compared to models fabricated from conventional impressions for dentate complete arches, a less clear conclusion can be drawn as to which method is superior. It is important to mention that for complete arch scans, unlike quadrants, scan pattern plays an important role (Latham et al. 2020; Mennito, Evans, Nash et al. 2019; Mennito et al. 2018; Müller et al. 2016; Oh et al. 2020). Ender and colleagues reported in 2016 that IOS systems exhibited better trueness than alginate or polyether impressions of complete arches, but fell short of PVS (Ender et al. 2016). In a more recent study, a fresh dentate cadaver maxilla was used. The specimen was scanned first with the ATOS scanner to make a reference standard model, and then scanned with 7 IOS systems, followed by CIs made using PVS (Mennito, Evans, Nash et al. 2019). This study found that many modern IOS systems performed as good as the CI group, which had a complete arch trueness of 37 µm. Recently, another study (Dutton, Ludlow, Mennito et al. 2020) evaluated complete arch trueness on a special reference standard model that contained teeth restored with gold, high translucency composite, low translucency composite, blue core, white core, amalgam, lithium disilicate and zirconia, in addition to natural teeth with dentin and enamel. They scanned this reference standard model with the ATOS Capsule and then with 7 IOS systems finding that, for some scanners, the material being scanned had no impact on accuracy, and that more modern scanners were able to achieve a complete arch trueness below 25 µm (Dutton, Ludlow, Mennito et al. 2020). Hence, while it cannot be said that every IOS is capable of making accurate full arch dentate impressions, several of the newest generation scanners are close or equal to the accuracy of a CI with PVS.

IOS: edentulous arches

Ten years ago, it was impossible to imagine that IOS systems would be used to scan edentulous arches. Nevertheless, it is not uncommon for clinicians to scan long span edentulous areas or even completely edentulous arches today (Figure 3). Scanners traditionally struggled with smooth edentulous areas, as these areas lack common distinct points of interest for the stitching algorithms to combine separate point clouds together. Hayama and colleagues found that scanners with larger head size performed better on edentulous areas (Hayama et al. 2018) (Figure 4). This is possibly due to a larger field of view being able to capture more distinct areas with more common overlap between scans. Interestingly, in this study all the IOS scanners performed truer than CI on a partially edentulous mandible reference standard model. Recently, the Primescan was found to be extremely accurate in vitro on soft tissues edentulous spans with a trueness of 24 µm and precision of 19 µm in edentulous arches (Schimmel et al. 2020). These values seem remarkably low for soft tissue. Contrastingly, another study found a trueness of 78 µm for the Primescan in edentulous arches, 145 µm for the Trios 3 and 182 µm for the Medit i500 (Cao et al. 2020). Of course, fake plastic tissue may scan very different than real tissue. Mennito and colleagues found in a cadaver study an interesting trend: physical impressions compressed the soft tissues by about 120 µm, while the scanners erred in the opposite direction by underestimating the soft tissues by 106-236 µm, depending on the scanner (Mennito, Evans, Nash et al. 2019). In a clinical study, Tregerman et al. found that removable partial denture frameworks made from intraoral digital impressions fit better than those made by conventional impressions (Tregerman et al. 2019). One of the authors (W.R.) currently has a paper in peer review reporting trueness and precision of scans of a completely edentulous fresh cadaver using different IOS systems. The results showed incredible accuracy for modern IOS systems on real soft tissues. However, better techniques still need to be established for capturing soft tissue borders and interocclusal records.

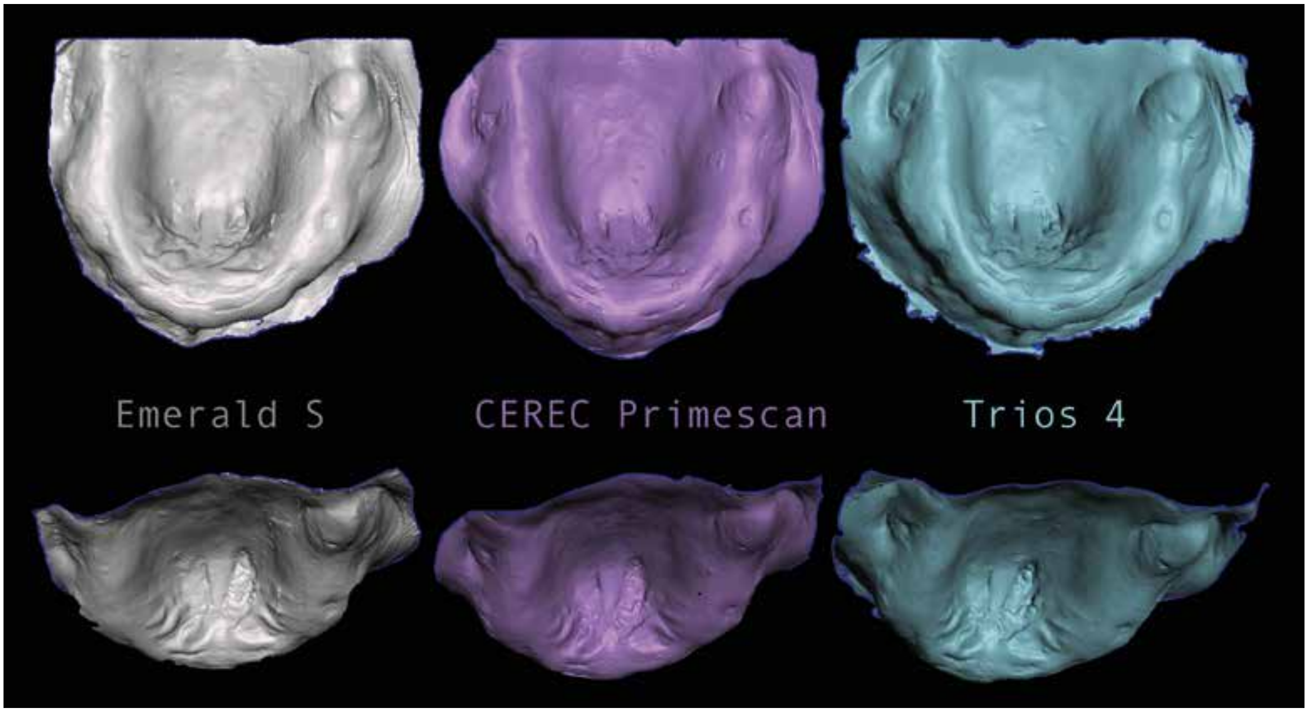

Figure 3.
The same patient scanned with 3 different IOS systems.

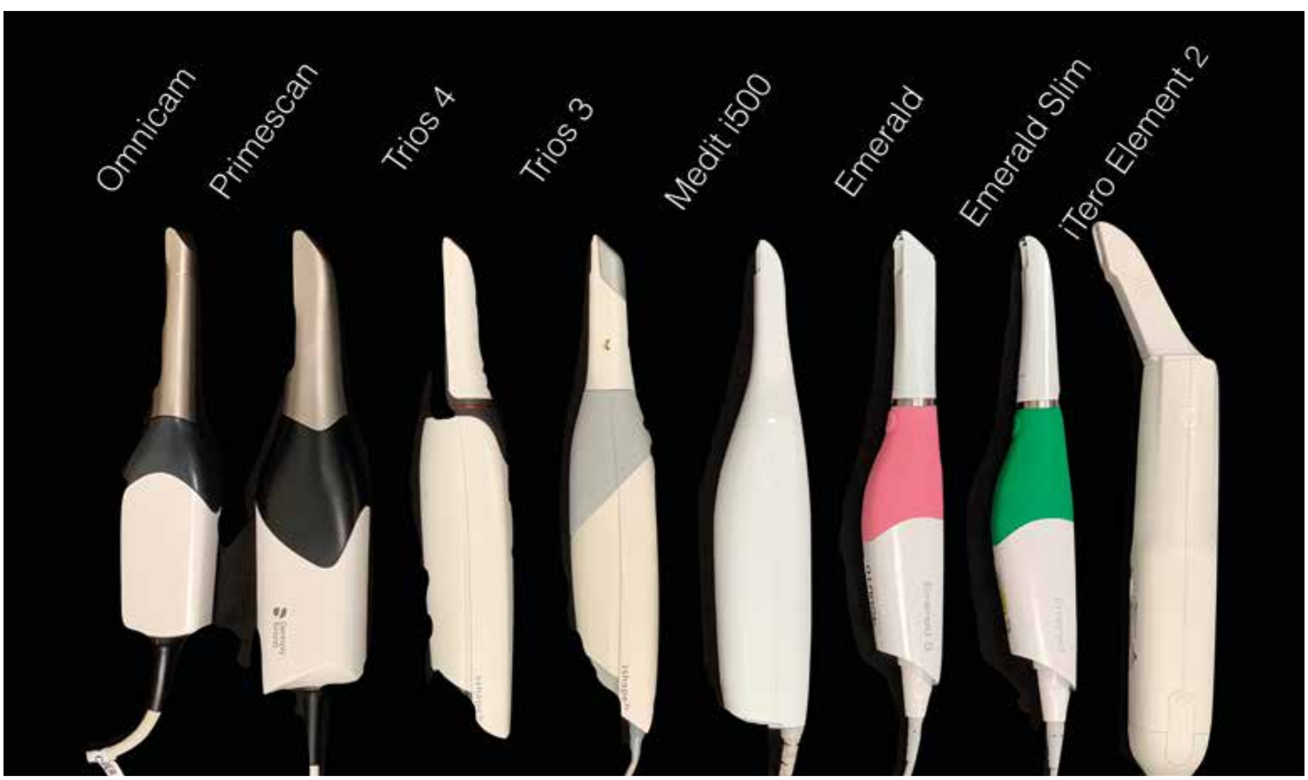

Figure 4.
Scanner tip sizes of various systems compared in a single photograph.

IOS: implants

Perhaps no area has been better researched than the accuracy of IOS systems on implant scan bodies. The primary focus in the literature is on complete arch implant scans with 4 to 6 scan bodies spanning the edentulous arch. Accuracy is the major concern when considering passive fits of definitive implant restorations, though not a lot of data exists on the accuracy needed to obtain passive fits for complete arch implant prosthetics and what deviation is acceptable clinically. In a clinical study Jokstad and Shokati found in a study using conventional techniques that misfits under 100 µm on full jaw fixed implant prosthetics still enabled prosthetic superstructure passivity, while misfits of 100- 230 µm, though not completely passive, had no real impact on clinical parameters such as peri-implant bone levels, observed after an average of 19 years of follow up in thirty patients (Jokstad and Shokati 2015). It is clear for complete arch implant cases that both scan body design and the scan pattern have an impact on the accuracy of models generated from IOS systems. Mizumoto and colleagues found a distance deviation greater than 170 µm and an angular deviation greater than 0.5 degrees in a maxillary model with 4 dental implant analogs (Mizumoto et al. 2020). Another study focused on smaller spans with less distance between scan bodies found deviations under 75 µm suggesting that IOS perform better when the distance is less between implants (Motel et al. 2020). Revilla-León et al. found even smaller deviations, with a trueness of 18.9 µm and 11.5 µm for two scan bodies tested on a partially edentulous typodont (Revilla-León et al. 2020c). In a randomized controlled trial comparing analog versus digital impressions for "All-on-Four" restorations, there was no difference in clinical outcomes at twelve months, with the digital impressions group being much more time efficient (Gherlone et al. 2016). In a recent systematic review, Wulfman and colleagues evaluated over 208 articles, concluding that optical impressions of multiple implants in edentulous patients may be as accurate as physical impressions of splinted copings (Wulfman et al. 2020). Thus, it appears that modern IOS systems are able to accurately scan complete arch implant supported prosthetics, and are as good as, if not better than, the gold standard splinted polyether open tray impression. Some clinicians are reluctant to believe that an IOS scan can be accurate enough for complete arch implant supported prosthetics and have adopted photogrammetry principles to help with accuracy (Bergin et al. 2013; Del Corso et al. 2009; Peñarrocha-Diago et al. 2017). Conflicting evidence exists in the literature and it is not clear if this stereophotogrammetry technology is needed, with some articles showing great results, and others showing actually worse outcomes than a standard IOS (Agustín-Panadero et al. 2015; Revilla-León et al. 2020a). Interestingly, in a recent study, the photogrammetry system tested provided the least accurate values, with the highest 3D discrepancy for the implant abutment positions amongst all the groups, while standard IOS scanning rendered much better outcomes (Revilla-León et al. 2020a). In summary certain IOS systems struggle more with long span edentulous spaces and extremely angled implants but overall clinical outcomes appear to be the same as with conventional techniques (Wulfman et al. 2020).

Figure 5.
Laboratory scanners are able to scan dentures for copy denture technique where an exact copy of a denture can be milled or printed.

Laboratory scanners

Extraoral scanners play an essential role for dental laboratories, digitizing analog impressions from practitioners to facilitate modern digital workflows. Laboratories are heavily incentivized to work digitally, as it reduces production costs and makes for a more efficient turnaround time, while being the only way to facilitate the ever-increasing number of prescriptions for things produced only through digital pathways, such as patient-specific implant solutions and monolithic zirconia crowns (Joda et al. 2017; Makhija, Lawson, Gilbert et al. 2016). Recently, laboratory scanners have been utilized to scan dentures for copy denture workflows allowing accurate replicas of existing dentures to be made (Figure 5). Just as with IOS systems, not all laboratory scanners perform equally. Evaluation of eight different laboratory scanners found scanners with blue light to perform better than laser or white light scanners, with variability in trueness ranging from 17µm to 33 µm for a complete arch reference standard model (Emir and Ayyildiz 2019). An older study by Bohner and colleagues found no significant differences in trueness between intraoral and extraoral scanners (Bohner, De Luca Canto, Marció et al. 2017), while another study found intraoral scanners to be most accurate for capturing prepared anterior abutment teeth regardless of tooth preparation geometry when compared to extraoral scanners and conventional PVS impressions (Carbajal Mejía et al. 2017). Some of the devices in the newest generation of intraoral scanners are within the same range of deviation as modern laboratory scanners for complete arches (Emir and Ayyildiz 2019).

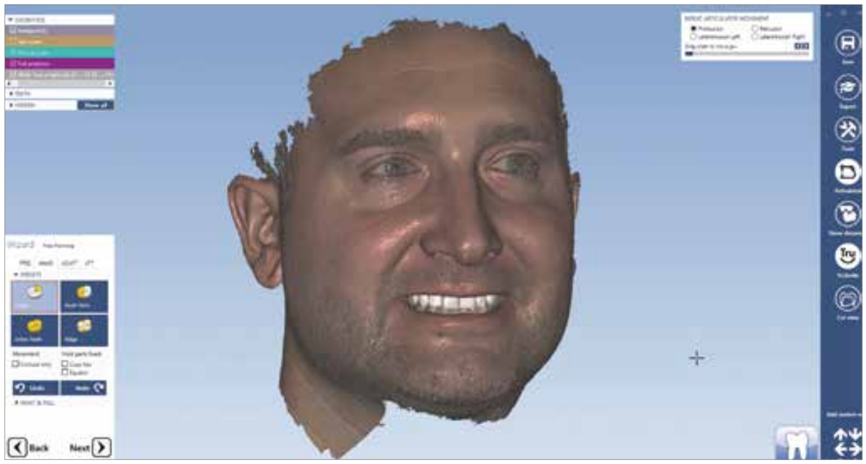

Figure 6.
Face scan here was generated using the Atec Space Spider and a new smile was sculpted in exocad. This provides real time 3D visualization and analysis of the smile design in the patient's face.

Facial scanners

Facial scanners are becoming popular as a way to make records as facial morphology. Facial analyses are important for various disciplines, such as oral maxillofacial surgery, orthodontics and prosthodontics (Figure 6). In the past, facial analysis included two-dimensional (2D) photographs, a Vernier caliper, and bevel protractor to painstakingly measure facial proportions (Berlin, Berssenbrügge, Runte et al. 2014). Thankfully, this analog process is being replaced with 3D face scans that can be directly incorporated into modern CAD software (Figure 3) (Huang et al. 2016). There is a wide disparity in the quality and price of facial scanners, making it difficult to draw evidence-based conclusions on accuracy. Some scanners incorporated on smartphones use LIDAR and photogrammetry, while others are industrial metrology scanners that cost more than modern laboratory scanners. Amornvit and Sanohkan compared 4 different devices, including an iPhone X, an industrial scanner, and an integrated face scanner on a CBCT. The expensive industrial scanner was the only one that performed accurate enough to be clinically useful (Amornvit and Sanohkan 2019). Recently, dental specific systems have been released in an attempt to increase accuracy and decrease cost. Piedra-Cascón et al. found the Bellus 3D Face Camera Pro to have a trueness of 0.91 µm when compared to the digital caliper measurements of facial anthropometric landmarks (Piedra-Cascón et al. 2020). This is a sufficient level of trueness to be very useful for planning large facially driven restorative cases. In the future, it is expected that the level of trueness from these handheld extraoral scanners will rival that of modern laboratory scanners.

CONCLUSION

THE ACQUISITION OF DATA with surface scanners now meets or exceeds the accuracy of traditional methods for most clinical applications. In addition to excellent accuracy, intraoral scanning systems provide significant advantages over analog impressions, including being more patient friendly, more cost and time effective, and allowing for seamless integration with modern manufacturing workflows, which are decidedly digital. A few obstacles remain with respect to edentulous arch/span workflows and truly integrated facially-driven treatment planning, but it is only a short matter of time before digital data acquisition becomes the rule, rather than the exception, for the diagnosis and treatment of patients in dental practices.

CLINICAL RELEVANCE

USING AN INTRAORAL SCANNER allows clinicians not only to obtain the same or higher level of accuracy compared to traditional impressioning methods, but also provides them with more efficient, patient-friendly outcomes, as well as access to digital workflows that greatly expand their diagnostic and treatment capabilities to optimize patient care.

IMPLICATIONS FOR RESEARCH

CURRENT CAPABILITIES OF SURFACE SCANNERS already largely meet or exceed those of their analog counterparts. Future research should be directed towards areas still needing improvement, such as the capture of dynamic tissues, edentulous borders, edentulous interocclusal records, along with the full integration of facial scanning with intraoral and CBCT data. Improvements in software for ease of use and harmonious integration of chairside, laboratory and implant planning programs will undoubtedly lead to an exponential growth in the adoption of digital scanners.

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