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Evaluation of the Accuracy of Six Intraoral Scanning Devices: An in-vitro Investigation.

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The making of conventional dental impressions of tooth preparations using elastomeric materials is a task encountered routinely in today's practice of dentistry. However, studies have evidenced that many of these conventional dental impressions that are sent to dental laboratories are unsatisfactory due to flaws such as voids and bubbles at critical regions of the impression.[1,2] Moreover, distortion and expansion of gypsum, used in the making of stone dental casts, can further reduce the accuracy of this conventional dental restoration fabrication process.[3] Because computer-aided design/computer-aided manufacturing (CAD/CAM) requires digital models, the interest in intraoral digital impression making has increased to circumvent the conventional production of stone casts using conventional impression materials.

Today, intraoral digital impression making of tooth preparations for the CAD/CAM-based fabrication of dental prostheses can be accomplished with a number of available systems now in the marketplace. Digital intraoral acquisition systems allow the dentist to capture the surface of the prepared teeth intraorally in three dimensions, enabling an almost completely digital workflow. CAD/CAM dentistry has transformed and revolutionized the way dentistry is practiced. Currently, all of the various chairside intraoral digital scanning devices are based on optical principles such as blue light-emitting diodes, blue laser technology, multiple single images that are stitched together, and continuous acquisition (streaming) of optical images. Differentiating factors include the need for the use of reflective powder to capture the image. The first chairside CAD/CAM system, CEREC (Sirona Dental Systems, Bensheim, Germany), was developed over 30 years ago at the University of Zurich.

The present study focuses on the accuracy of six currently available intraoral scanners in their ability to accurately scan a single molar abutment tooth in-vitro. Additionally, a brief overview of each scanning device is provided.

Materials and Methods

To investigate the accuracy of various intraoral scanning systems the following six scanners were studied: the iTero (Align Technology, San Jose, CA), the True Definition (3M ESPE, St. Paul, MN), the PlanScan (Planmeca/E4D Technologies, Richardson, TX), the CS 3500 (Carestream Health, Rochester, NY), the TRIOS (3Shape A/S, Copenhagen, Denmark), and the CEREC AC Omnicam (Sirona Dental Systems, Bensheim, Germany) (Table 1). An acrylic (self-curing denture acrylic, Lang Dental Manufacturing Co., Inc., Wheeling, IL) replica of a typodont dental model (Nissin Dental Product, Kyoto, Japan) was fabricated. Typodont teeth (Simple Root Tooth Model, Permanent Tooth [A5A-200], Nissin Dental Product, Kyoto, Japan) were embedded into the fabricated acrylic model, and the first right maxillary molar was prepared for an all-ceramic crown (Fig. 1). The model was scanned with an industrial grade, highly accurate reference scanner (ATOS Blue Light Triple Scan III, 8 megapixel with a 100 mm lens set, GOM mbh, Braunschweig, Germany) in order to create a digital reference dataset. Additionally, the acrylic model with the embedded typodont teeth was scanned on three separate occasions by a single trained, experienced dentist (S.P.) with each of the six scanning systems.

Table 1. List of Evaluated Products

Scanning System	Manufacturer
iTero	Align Technology San Jose, CA
True Definition	3M ESPE St. Paul, MN
PlanScan	Planmeca/E4D Technologies Richardson, TX
CS 3500	Carestream Health Rochester, NY
TRIOS	3Shape A/S Copenhagen, Denmark
CEREC AC OmniCam	Sirona Dental Systems Bensheim, Germany

Figure 1: Reference model with the embedded artificial tooth.

A specific scan order was employed to avoid any contamination of the reference model due to the necessary application of a reflective powder, which is needed for the 3M True Definition Scanner. All of the datasets (STL file format) were loaded into three-dimensional (3D) evaluation software (Geomagic Qualify 2013, Morrisville, NC). After loading, the crown preparation was digitally isolated, and all areas not relevant to the present study were removed. The scanners were evaluated in terms of trueness and precision. For the trueness measurements, the digital datasets obtained from the scanners were superimposed (best-fit algorithm of the software) to the reference dataset, and 3D comparisons were performed (n=3/intraoral scanner). For the precision measurements, each dataset from a scanner was superimposed onto the other two obtained datasets for that specific scanner (n=3/intraoral scanner; 1 to 2, 1 to 3, 2 to 3), and evaluated for 3D deviations.

Statistical analyses

For descriptive analyses means, medians and standard deviations (SDs) were computed. Furthermore, boxplots are used for a graphical presentation of the data. Linear mixed models with random intercepts for each scanner were fitted to evaluate device effects response variables. Scheffe's Method was applied for *p*–value adjustment due to several pairwise comparisons (multiple testing issue). All calculations were performed with the statistical software STATA 13 (StataCorp LP, College Station, TX).

Scanners

iTero

The iTero intraoral scanner utilizes parallel confocal imaging technology to capture a color 3D digital impression of the tooth surfaces, contours, and surrounding gingival tissues. The system captures up to 3.5 million data points per arch scan. The scanner has the ability to capture preparations for crowns, bridges, inlays, veneers and onlays. During scanning, a series of visual and verbal prompts are given, which help to guide the clinician through the scanning process. For each preparation, a facial, lingual, mesio-proximal, and disto-proximal view is recorded in approximately 15–20 seconds, after which the adjacent teeth are scanned from the occlusal, facial and lingual aspects. The iTero system is only used for digital impression making and does not come with a dedicated milling machine, although its open platform can integrate with design software and third-party milling units. If required, it is possible to obtain milled iTero CAD/CAM resin (polyurethane) models.[4,5]

3M True Definition

The 3M True Definition Scanner also offers an open platform and the ability to connect to a certified design software and chairside milling machine. The 3M system uses a blue LED light and a video imaging system to capture the data and create a virtual model. By moving the scanner over the tooth surfaces, the video feed develops the digital dental model. The clinical technique used with the 3M system requires proper isolation of the desired area to be captured, as well as a light dusting of the teeth with a titanium oxide reflective powder. Regardless of the need for powdering, this digital impression system has been previously shown to be very accurate.[6–9] After scanning of the teeth and the creation of the virtual model, the acquired data is sent to 3M for processing and available for download in an open file format. If required, a physical dental model, based on stereolithographic manufacturing technology, can be obtained from the manufacturer[4,5]

PlanScan

The Planmeca PlanScan (driven by E4D Technologies) system is designed to be used in a similar manner to Sirona's CEREC systems, as it can be used as a digital impression system, as well as a chairside design and milling system. The PlanScan system uses blue light with real time laser video-streaming technology to capture the dental data, and is a powder-free system. The system captures both hard and soft intraoral tissues of various translucencies, dental restorations, as well as stone models and conventional impressions. Removable scanner tips, with built-in heated mirrors, allow no down time between patients, as well as a high level of disinfection. The Planmeca PlanCAD Design Center includes scanning software, design software, a mouse and a laptop. The digital models can be used to design inlays, onlays, crowns, bridges and veneers.

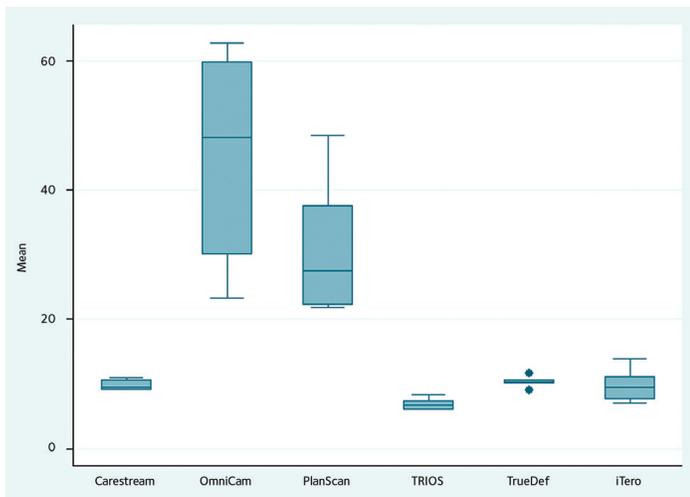Figure 2: Absolute mean deviations by intraoral scanner for the trueness measurements.

Figure 3: Absolute mean deviations by intraoral scanner for the precision measurements

If needed, the scans can be sent to the laboratory for processing, designing and manufacturing of the restoration, or the restorations can be milled chairside using PlanScan's dedicated PlanMill 40 milling machine.

CS 3500

The CS 3500 intraoral scanner is one of the latest available powder-free intraoral scanners that enable dental professionals to scan patients' teeth to create color 3D images. Similar to the CEREC BlueCam, it is a click-and-point system. Thus, it requires the user to keep the wand still during capturing. Additionally, adequate overlapping of the single images (≥ 50% of the previous image) is essential. The scanner can be used to design crowns, bridges, inlays, onlays, and veneers utilizing its CS Restore software, and milled with the optional dedicated Carestream milling machine (CS 3000), or the data can be sent to a laboratory for the design and milling of the restorations. The colored 3D images help in drawing the margin lines, as one can more easily identify the differences between the natural tooth structure and the gingival tissues. A light guidance system allows the user to focus on the acquisition of the image by looking directly in the patient's mouth, and not necessarily on the monitor screen.[4]

TRIOS

The TRIOS scanner is a powder-free, open file system based on ultrafast optical scanning technology. In its current version, the TRIOS scans in color (in the present study the investigated scanner was the predecessor, the black-and-white version). Again, color scanning allows the clinician to more easily identify the preparation margins. The TRIOS system automatically reads the shades of the adjacent teeth while scanning and
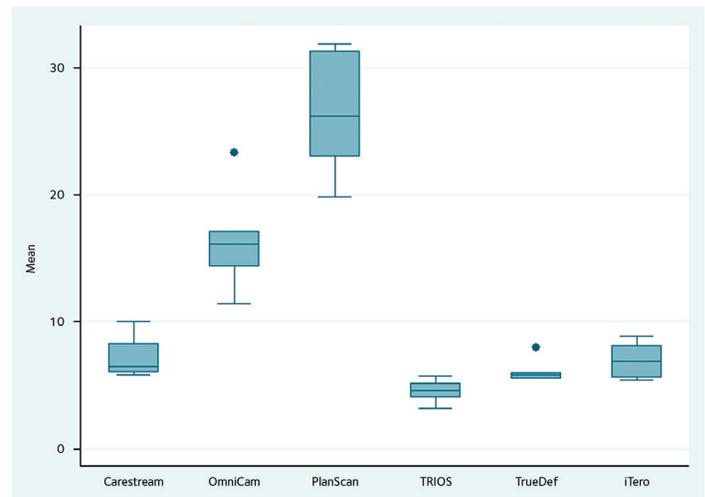
provides this information along with the digital impression. Therefore, shade matching is now automated with this system, which also takes digital intraoral photographs, thus allowing the acquisition of high-definition photos for documentation or communication purposes. Unwanted objects (tongue, cheeks or lips) are detected automatically and digitally removed from the digital impression in real time. The TRIOS POD solution is now an alternative to the cart format allowing greater mobility, and is similar to the PlanScan device that uses a laptop into which the scanner is plugged via a USB port.[4,5]

CEREC AC OmniCam

Sirona's CAD/CAM technology has the longest track record of any of the existing digital impression systems. The CEREC system has been in existence, in one form or another, for the past 30 years. Sirona's most recent system is the CEREC AC with OmniCam released in the summer of 2012. In the predecessors, imaging was done via stitching together individual images creating a monochromatic yellow stone-like digital cast. However, the new OmniCam captures images without the use of powder via digitally streaming to create a full-color digital cast.

For this study we used Sirona's 4.3 software. Sirona's new 4.4 software utilizes a bio-statistical procedure to calculate the entire jaw, and we will be reevaluating the OmniCam utilizing this updated software when available.

Results: Evaluation of the Accuracy

In total, 18 datasets (three per intraoral scanner) were evaluated for trueness and precision values.

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The smallest deviations for the trueness measurements (± standard deviation) between the reference dataset and the various intraoral scanner datasets were obtained from the TRIOS (6.9 ± 0.9 µm), followed by the CS 3500 (9.8 ± 0.8 µm), the iTero (9.8 ± 2.5 µm), the True Definition (10.3 ± 0.9 µm), the PlanScan (30.9 ± 10.8 µm), and the CEREC OmniCam (45.2 ± 17.1 µm) (Fig. 2). Statistically significant differences were detected between the CS 3500, the TRIOS, the True Definition, the iTero, and the CEREC Omnicam as well as between the CS 3500, the TRIOS, the True Definition, the iTero, and the PlanScan ($p <.05$).

Precision values were identified to be most accurate for the TRIOS (4.5 ± 0.9 µm), followed by the True Definition (6.1 ± 1.0 µm), the iTero (7.0 ± 1.4 µm), the CS3500 (7.2 ± 1.7 µm), the CEREC OmniCam (16.2 ± 4.0 µm), and the PlanScan (26.4 ± 5.0 µm) (Fig. 3). Statistically significant differences occurred between all scanners and the CEREC OmniCam and between all scanners and the PlanScan ($p <.05$).

Discussion

Accuracy values for the various scanners were identified via the obtained datasets of the single tooth scans. To minimize the risk of any inter-operator influence, only one experienced investigator, familiar with all the scanning devices, performed the scans. As identified in previous studies,[7] it is possible that technological aspects might have influenced the final accuracy of the datasets. The iTero scanner, for example, uses parallel confocal imaging technology, with an array of incident red laser light beams to capture color images of dental hard tissues and the surrounding soft tissues.[4,5,10] It is important to maintain the scanning wand at a certain focal distance while scanning. 3M's True Definition Scanner utilizes video technology using a pulsating visible blue light.[4,5] This device requires a reflective powder dusting of the surfaces to be captured. However, this powdering process appears to not have influenced the accuracy of this device. The PlanScan uses blue laser technology with wavelengths of 450 nm during its video rate scanning. Its wand has to be moved smoothly while hovering above the object to be scanned, or supported by adjacent structures at a certain focal distance. One of the recently released intraoral scanners is the CS 3500 from Carestream. Rather than the current trend of using real-time video technology for capturing purposes, as with the True Definition Scanner, the PlanScan, the TRIOS, and the OmniCam, the CS 3500 is designed as a point-and-click system. Resting the scanning wand on adjacent structures at a certain focal distance is important.[4] The TRIOS intraoral scanner is based

on confocal microscopy capturing multiple images in a very short amount of time. Its wand needs to be hovered over the structures to be captured.[4,5,11] This technology, in combination with the wand design, seems to be beneficial for capturing high quality datasets with excellent trueness and precision values. The CEREC OmniCam is a powder-free, full color scanning system. It utilizes active triangulation and emits light of different wavelengths to measure surfaces. The CEREC Omnicam is based on video technology capturing a smooth model while hovering the wand above the teeth.[4] As opposed to the other systems, the CEREC workflow is still a closed one, in other words, open STL files are not natively available. Therefore, it was necessary to convert the obtained datasets from the Sirona specific formats to the open format in order to perform the comparisons. It was not possible to identify any reason why the trueness and precisions values of the OmniCam and the PlanScan are significantly, however, still clinically acceptable, varied from the other four scanners. It is very likely that technology related differences lead to these deviations.

Comparing the results of the present study with the relatively few previously published papers on the accuracy of single-tooth digital impressions, revealed a significant increase in the accuracy found in the current study. Previous studies reported trueness values of 19.2 µm and 27.9 µm, and precision values of 10.8 µm,[12,13] as compared in the present study, which determined trueness values as accurate as 6.9 µm and precision values as accurate as 4.5 µm. It is difficult to identify precisely why these deviations exist between the present study and those of the previously reported values. Possible explanations might include slightly different study designs (reference models, reference scanners), but more likely, recent improvements in the devices may be the primary reason for the more accurate datasets found in the present study.

Finally, one has to consider that the results of the present study were based on an in-vitro study design. In an in-vivo setting, the results might be different due to the presence of blood, saliva, and patient movements. Further, the obtained results on the accuracy of digital intraoral impression making does not provide any information about the quality of a fabricated restoration based on these digital datasets.

All scanners (except the OmniCam) evaluated in this project have an open architecture, which means that the acquired digital files can be transferred with an open connection that allows the laboratory to use virtually any CAD/CAM system for the fabrication of restorations. This increases the flexibility and versatility of the process.

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CAD/CAM units with closed software programs use files that can only be transferred and used for specific devices. Different types of scanners have different attributes, as do the programs supporting digital impression making, however, all six studied scanners are designed to scan crowns, bridges, veneers, inlays, and onlays.

Conclusion

Within the limits of the present study, all of the six investigated scanners produced clinically acceptable results in terms of accuracy. The small observed differences might be related to technological aspects of each device. Further, additional deviations can be expected in the oral environment due to saliva, blood and patient movements.

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