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SYSTEMATIC REVIEW

Accuracy of digital technologies for the scanning of facial, skeletal, and intraoral tissues: A systematic review

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ABSTRACT

Statement of problem. The accuracy of the virtual images used in digital dentistry is essential to the success of oral rehabilitation.

Purpose. The purpose of this systematic review was to estimate the mean accuracy of digital technologies used to scan facial, skeletal, and intraoral tissues.

Material and methods. A search strategy was applied in 4 databases and in the non–peer-reviewed literature from April through June 2017 and was updated in July 2017. Studies evaluating the dimensional accuracy of 3-dimensional images acquired by the scanning of hard and soft tissues were included.

Results. A total of 2093 studies were identified by the search strategy, of which 183 were initially screened for full-text reading and 34 were considered eligible for this review. The scanning of facial tissues showed deviation values ranging between 140 and 1330 µm, whereas the 3D reconstruction of the jaw bone ranged between 106 and 760 µm. The scanning of a dentate arch by intraoral and laboratorial scanners varied from 17 µm to 378 µm. For edentulous arches, the scanners showed a trueness ranging between 44.1 and 591 µm and between 19.32 and 112 µm for dental implant digital scanning.

Conclusions. The current digital technologies are reported to be accurate for specific applications. However, the scanning of edentulous arches still represents a challenge. (J Prosthet Dent 2019;121:246-51)

Digital techniques have been applied in dentistry to simplify oral rehabilitation procedures. The acquisition of 3-dimensional (3D) images of oral structures has made it possible to virtually define treatment planning, to design and mill restorations, and to monitor the result of surgical and restorative procedures.[1-5] Different technologies have been used to create virtual images, and their application differs according to the scanned tissue. Facial scanners are used to scan extraoral soft tissues, intraoral and laboratory scanners digitize the intraoral arch, and computed tomography (CT) scanning provides bone imaging.[5-8] In addition, a virtual patient may be obtained based on the superimposition of facial, skeletal, and intraoral imaging.[9,10]

The accuracy of digital-based techniques has been reported for dental implants[11] and restorative procedures.[12,13] However, the accuracy differs according to the device and clinical application.[14-16] For instance, Patzelt et al[14] showed that not all the scanners evaluated could be used to scan edentulous jaws, whereas Jeong et al[16] reported that the accuracy of digitizing the complete dental arch depends on the scanner technology. The same concern affects the 3D reconstruction of the maxilla and mandible scanned by cone beam computed tomography (CBCT) devices.[17] Thus, the results are still

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Clinical Implications

Digital technologies are sufficiently accurate to provide virtual images of soft and hard tissues. The main challenge remains for the scanning of edentulous arches.

controversial, and a single study may not reproduce the true clinical accuracy provided by these technologies.

Factors that may be related to the appearance of discrepancies include the digitizing environment, scanning strategies, and data processing.[18] If the scanned images are not accurate, treatment failures may occur, including errors during surgical treatment planning, misfit of dental restorations, and the milling of inaccurate surgical guides used for dental implant treatment. Hence, the accuracy of digital images is essential to the result of the treatment. A question that still remains is ”How accurate is the virtual patient?” The purpose of this systematic review was to determine the accuracy provided by the digital technologies currently used in a clinical setting.

MATERIAL AND METHODS

This study was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[19] and was registered at the International Prospective Register of Systematic Reviews (PROSPERO) under the protocol number 42017060836.[20] The study selection was based on the definition of ‘accuracy’ provided by Tapie et al.[18] Accuracy was determined as the agreement between the experimental and the reference data set, explained by both the closeness to the reference data set (trueness) as the agreement within repeated measurements (precision). Dimensional accuracy was described by means of deviation/discrepancy values.

Inclusion criteria consisted of studies evaluating the accuracy of 3D facial, skeletal, and intraoral imaging compared with a reference model. Conversely, reviews, letters, abstracts, case reports, or studies in which the accuracy could not be determined were not considered for analysis.

A main search strategy was formulated and applied in the PubMed (MEDLINE) database (Table 1). Furthermore, individual search strategies were formulated using the main search as the reference and applied in the Science Direct, Scopus, and Cochrane databases (Supplemental Table 1). In addition, the non−peer-reviewed literature was assessed on ProQuest, Scholar Google, and OpenGrey sources. All searches were conducted between April and June 2017 and updated in July 2017.

Two independent reviewers (L.B., D.G.) participated from the first phase of study selection by choosing articles based on the information provided in the title and abstracts. When all inclusion criteria items were described, articles were selected for full-text reading, and articles considered eligible for review were selected.

Table 1. Main search strategy

Search strategy	Key words	Screened articles
#1 AND #2 AND #3	((((((((((“virtual patient”) OR ”virtual casts”) OR “virtual model”) OR “digital casts”) OR “digital models”) OR “3-D dimensional surface”) OR “digital denture”) OR “digital imaging”) OR “computer simulation” [MeSH Terms]) OR “computer-assisted therapy” [MeSH Terms]) AND (((((((((((((((((((scanner) OR “intraoral scan”) OR “laboratory scan”) OR “facial scan”) OR “digital impression”) OR “indirect capturing”) OR “direct capturing”) OR digitalization) OR “3D surface scanning”) OR “cone beam computed tomography”) OR CAD-CAM [MeSH Terms]) OR “computer-aided design”) OR interferometry) OR “structured light method”) OR “moir fringe method”) OR stereophotography) OR photogrammetry) OR “white-light scanner”) OR “optical scanners”) AND ((((((((“dimensional measurement accuracy” [MeSH Terms]) OR accuracy) OR precision) OR trueness) OR feasibility) OR reliability) OR “3D comparison”) OR “data accuracy” [MeSH Terms])	1210
#3	((((((((“dimensional measurement accuracy” [MeSH Terms]) OR accuracy) OR precision) OR trueness) OR feasibility) OR reliability) OR “3D comparison”) OR “data accuracy” [MeSH Terms])	632686
#2	(((((((((((((((((((scanner) OR “intraoral scan”) OR “laboratory scan”) OR “facial scan”) OR “digital impression”) OR “indirect capturing”) OR “direct capturing”) OR digitalization) OR “3D surface scanning”) OR “cone beam computed tomography”) OR CAD-CAM [MeSH Terms]) OR “computer-aided design”) OR interferometry) OR “structured light method”) OR “moir fringe method”) OR stereophotography) OR photogrammetry) OR “white-light scanner”) OR “optical scanners”)	86925
#1	((((((((((“virtual patient”) OR ”virtual casts”) OR “virtual model”) OR “digital casts”) OR “digital models”) OR “3-D dimensional surface”) OR “digital denture”) OR “digital imaging”) OR “computer simulation” [MeSH Terms]) OR “computer-assisted therapy” [MeSH Terms])	222936

Data were extracted by the first reviewer (L.B.) and evaluated by the second reviewer (D.G.). In case of disagreement, a third reviewer (N.S.) was consulted. The following data were extracted from the eligible studies: the purpose of the study, study details, sample features, scanning methods, measurement details, findings, and conclusion.

The risk of bias assessment was performed using the Quality Assessment Tool for Diagnostic Accuracy Studies-2 (QUADAS-2).[21] The tool comprised questions related to 4 domains: patient selection, index test, reference standard, and flow and timing. Only questions considered relevant for the eligible studies were selected. The analysis was performed using software (RevMan 5.3; The Nordic Cochrane Centre).

RESULTS

The initial search resulted in 2903 articles, which was reduced to 2256 after removing duplicate reports. After study selection, 183 articles were screened for full-text

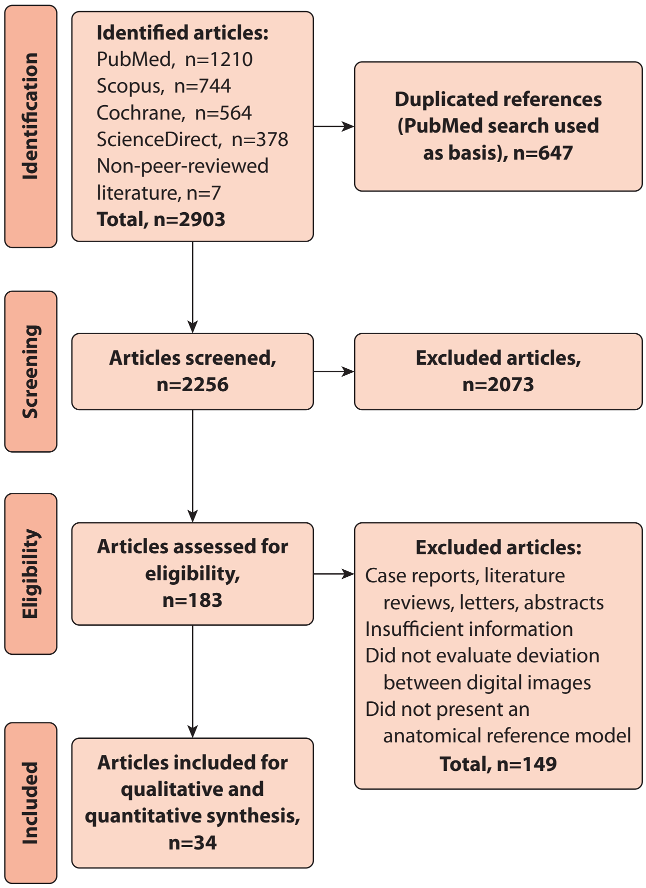

Figure 1. Search strategy.

reading, and 34 of these studies were considered eligible for this review (Fig. 1).

The eligible studies were organized according to the evaluated anatomic structure, and the study characteristics are described in Supplemental Tables 2-6. Three studies evaluated the accuracy of facial soft tissue scanning (Supplemental Table 2),[22-24] 4 studies evaluated the use of CBCT or CT to create 3D images of bone (Supplemental Table 3),[17,25-27] and 27 studies evaluated intraoral tissues. Of these, 5 studies scanned the complete intraoral arch (Supplemental Table 4),[14,16,28-31] 17 studies scanned prepared teeth (Supplemental Table 5),[32-48] and 4 evaluated digital implant impressions (Supplemental Table 6).[49-52] Most studies were in vitro experiments, which is justified by the fact that the image analysis comprised digital-based methods. Only 3 studies, in which the reference model was based on patient scanning, were performed clinically. Two of these evaluated the accuracy of facial scanners,[23,24] and 1 used an intraoral scanner to scan the complete maxilla.[30]

In general, the studies aimed to evaluate the accuracy of digital scanners,[17,22,23,29,30,34,36,40-46,48,50,52] to compare them with conventional methods,[32,34,35,37,38,47,49,51] or to assess the influence of external factors on scanning accuracy.[36,39] For facial scanning, the accuracies of digital stereophotogrammetry and interferogram techniques were compared in an in vitro study. Clinically, the following technologies were evaluated: photogrammetry, magnetic resonance imaging, and structured light scanners. Bone imaging was mostly acquired using CBCT, and only 1 study used CT.[17] Intraoral impressions were acquired by a range of laboratory and intraoral scanners.[28]

Facial scan analysis was performed considering only the middle third of the face in an in vitro study[22] and the whole face in clinical studies.[23,24] For CBCT and CT scans, all studies included the jaw. The complete dentition was scanned in 4 studies, whereas only 1 study scanned a completely edentulous model.[14] In evaluating the prepared teeth, 6 studies scanned the complete arch containing one or more prepared teeth,[32-34,37,38,45] 11 studies scanned the teeth individually,[31,36,39,41-48] and 2 studies used a partial scan.[35,40] For implant impressions, complete-arch scanning was performed for all studies.

In general, all studies presented a low risk of bias (Fig. 2). Patient selection was considered unclear for clinical studies for which the randomization process was not detailed.[53] For in vitro studies, the randomization process was not considered, whereas the avoidance of case-control design and inappropriate exclusions were considered as low risk. The reference standard was considered unclear when the scanner resolution used to obtain the reference image was not described. Conversely, when the scanner resolution was considered too small compared with the remaining studies[26] or when the reference value was obtained through reverse engineering, the risk was considered high.[36,44]

The patient and setting did not match the review question when the master model did not truly represent the complexity of a prepared tooth[39] or when the evaluated patient presented facial deformities.[23] The index test differed from the review question when the purpose of the study was to evaluate the influence of external variables in the scanning process.[26,36,43,51]

Facial scanners showed deviation values ranging between 140 and 1330 μm. For most the facial scanners, the accuracy was close to 500 μm, which was considered acceptable for clinical use.[53] Conversely, the accuracy of CBCT was influenced by the exposure parameters and ranged between 106 and 760 μm, whereas the deviation mean for CT was 137 μm.

For intraoral scanning, a high variability of deviation values was found among studies. The trueness for complete dentition scanning was between approximately 17 μm and 378 μm, whereas the precision was between 55 μm and 116 μm. For the edentulous model, trueness ranged between 44.1 and 591 μm, and precision was up to 698 μm. In general, all scanners were considered accurate for complete dentition scanning. However, for edentulous arch scanning, scanner accuracy is questionable because of high variability.

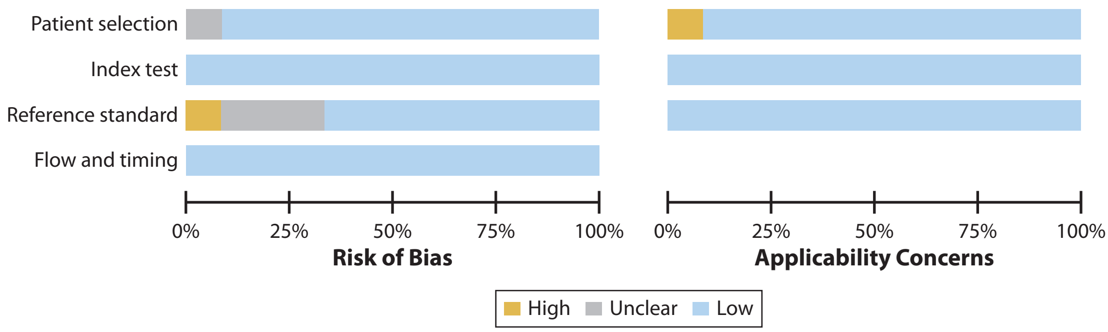

Figure 2. Qualitative analysis by Quality Assessment Tool for Diagnostic Accuracy Studies-2 (QUADAS-2)[21] tool.

For the prepared teeth, the minimal accuracy was 23 μm and achieved values close to 60 μm when the entire arch was scanned. However, if the prepared tooth was scanned alone, the studies showed an accuracy benchmark between 20 μm and 40 μm. The higher accuracy was reported by Jeon et al,[36] with deviations ranging between 6.2 and 21.8 μm. In addition, the accuracy was lower for molars than for canines or premolars. Guth et al[35] showed comparable accuracy values for the scanning of 4-unit dental prostheses. For dental implant digital scanning, a high variability was found among scanners, with deviations ranging between 19 μm and 112 μm among studies.[49-52] In addition, Mangano et al[50] showed similar values for partially and completely edentulous maxillas. The precision ranged between 30 μm and 220 μm.

DISCUSSION

Deviation values differed among studies according to the scanned tissue, being lower for prepared teeth and increasing for complete-arch scanning. The 3D reconstruction of jaw and facial tissue showed the highest discrepancies. However, the intended clinical application will define whether high or low accuracy is required. When the same scanned tissue was considered, studies showed that accuracy was influenced by the scanner technology, object shape, and scanning strategies. In general, most scanners had accuracy values that were acceptable for clinical use.

Facial scanners are used for treatment planning and outcome assessment.[53,54] The eligible studies included in the present review reported deviation values close to 1 mm. However, a discrepancy up to 2 mm is considered clinically acceptable.[24] When different technologies were compared, stereophotogrammetry and white light scanners showed similar accuracy,[23] and this was higher than that of magnetic resonance imaging and infrared scanners.[24] In addition, Artopoulos et al[22] showed an experimental moiré profilometry with similar accuracy to stereophotogrammetry when scanning the middle third of the face.

Conversely, 3D models derived from CBCT technology are used for different applications, including dental implant or orthognathic surgery planning, prototyping, and bone dimension measurements.[24] Although the CBCT was less accurate than the CT, it was reported to be clinically acceptable, because the mean deviations were lower than 0.4 mm. The accuracy seems to be affected by the exposure parameters and the appearance of image artifacts. Matta et al[17] showed that a voxel size of 0.2 mm resulted in higher accuracy than 0.3-mm and 0.4-mm voxel sizes. The image artifacts responsible for decreasing the accuracy were located at the mandibular borders and lingual and posterior sites. The presence of artifacts in these regions does not hamper the implant planning or the detection of important anatomic structures.[25,26]

For intraoral scanning, higher discrepancies were found when the complete dentition was evaluated. However, for prepared teeth, the scanners provided similar accuracy when teeth were scanned for single crowns or fixed partial dentures, as well as for partial and complete-arch scanning. The higher discrepancy variability found for dental implants may be because all studies evaluated edentulous models, which affects scanning accuracy.[15] Similarly, Patzelt et al[14] showed high discrepancies for the scanning of patients with complete edentulism, and the authors did not recommend the use of intraoral scanners for these patients. The mobile tissues and the lack of reference landmarks probably lead to these discrepancies.[14,41] Kim et al[41] reported that the presence of landmarks in an edentulous space improves scanning.

A limitation of this systematic review is the fact that the findings of eligible studies cannot be directly correlated with clinical outcomes, because different factors are related to the final result of the treatment. To the best of the authors' knowledge, whether a deviation between the virtual image and the physical structure will result in clinical failures cannot yet be predicted; further studies correlating deviation values to clinical outcomes should be performed to answer this question.

CONCLUSIONS

Based on the findings of this systematic review, the following conclusions were drawn:

1. Current scanning technologies offer an acceptable accuracy for specific applications, although this depends on the scanner technology, object shape, and scanning strategies.
2. The scanning of the edentulous arch still represents a clinical challenge.

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Noteworthy Abstracts of the Current Literature

Antifungal and mechanical properties of tissue conditioner containing plant-derived component: An in vitro study

Naito Y, Yumoto H, Kumar Hs K, Matsuo T, Hirota K, Miyake Y, Nagao K, Tomotake Y, Jimbo R, Ichikawa T

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Purpose. To evaluate the antifungal activity and mechanical properties of a novel antifungal tissue conditioner containing Juncus powder.

Material and methods. Juncus powder was mixed with GC tissue conditioner at concentrations of 2.5%, 5.0%, and 10.0% by mass. The cylindrical specimens of Juncus-mixed tissue conditioner (dimensions: 10 mm in diameter and 2 and 6 mm in height for antimicrobial and mechanical tests, respectively) were prepared. The specimens placed on the bottom of the 24-well tissue culture plate were cultured with Candida albicans CAD1 for 2 and 4 days. The proliferation of the C. albicans in the wells was determined by measuring the optical density of fungal culture, and the surface of the specimens were also observed by scanning electron microscopy (SEM). To assess the mechanical properties of the specimens, the fluidity and hardness of Juncus-mixed tissue conditioner were measured using the methods certified according to ISO 10139-1.

Results. Juncus-mixed tissue conditioner significantly exhibited growth inhibitory effect in a Juncus concentration-dependent manner after both 2- and 4-day cultures. SEM observation showed that the amount of C. albicans on Juncus-mixed specimens drastically decreased, and biofilm formation was markedly inhibited. Moreover, both mechanical properties were found to be within the ranges regulated and specified by ISO.

Conclusions. These findings demonstrated that the tissue conditioner including Juncus powder has a significant growth inhibitory effect against C. albicans, and it is suggested that the application of Juncus-mixed tissue conditioner may prevent denture stomatitis and oral candidiasis in denture wearers.