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Accuracy of Intraoral Scanners: A Systematic Review of Influencing Factors

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ABSTRACT

Digital impressions by intraoral scanning (IOS) have become an increasingly popular alternative to conventional impressions. This systematic review aimed to evaluate the accuracy of the available IOS systems for dental impressioning, and to identify the influencing factors on accuracy. The literature search was completed to retrieve all the studies that investigated the IOS accuracy when used to scan teeth. A total of 2305 studies were initially obtained. After applying the inclusion criteria, 32 studies were suitable for the analysis. The following systems were included in the review: Cerec Bluecam, Cerec Omnicam, Cadent iTero, Lava C.O.S, Lava True Definition, TRIOS, TRIOS Color, E4D, Planscan, MHT, Carestream 3500 and Zfx IntraScan. In comparison to conventional impressions, the IOS systems can be reliably used for diagnostic purposes and short-span scanning. However, for whole arch scanning, the IOS is susceptible for more deviation. The studies indicated variable outcome of the different IOS systems. While the accuracy of IOS systems appears to be promising and comparable to conventional methods, they are still vulnerable to inaccuracies. For prosthesis fabrication, the IOS accuracy is enhanced by reducing the span of scanning, and ensuring the scanned surfaces exhibit minimal irregularities.

INTRODUCTION

Dental impression is a routine procedure that is required in many disciplines of dentistry to record the oral tissues. The generated casts are used for diagnostic purpose, treatment planning, or prosthesis and appliance fabrication. In order for the impression to serve its purpose, it has to accurately represent oral tissues of the patient. Inaccurate impression will lead to prosthesis misfit which will eventually cause cement dissolution, loss of prosthesis retention, and rendering the tooth prone to biological problems such as caries.[1,2] In addition, imprecise surface details will prevent precise articulation and occlusion establishment.[3]

Although the conventional impression has been the standard of practice for many decades, it is associated with material preparation, ongoing cost, technical time, potential patient discomfort, and requirements of high clinical skills.[4,5] Regardless of the material and technique, any conventional impression is associated with an inevitable degree of error which is attributed to the number of steps and materials manipulation.[4-6] For example, all impression materials are prone to dimensional distortion through the setting procedure.[6,7] As the impression is removed from the patient's mouth, unavoidable deformation will occur with removing the impression from the undercut areas. Likewise, pouring the impression will further contribute to the distortion during the setting of the stone material. Yet, the potential accuracy problems are offset by the familiarity of taking the impression and pouring it with dental stone.[6]

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Since the 1970's, the interest had emerged to employ computer-aided design and computer-aided manufacturing (CAD/CAM) to fabricate dental prostheses. More recently, digital dentistry had received significant refinements[8] and many systems are available in the market for chairside digital impression and prosthesis fabrication.[4,5,9-11] A significant aspect of chairside CAD/CAM is the implementation of intraoral scanning (IOS). Contrary to conventional impressions, the IOS impressions have the advantage of omitting the need for impression materials, trays and cast pouring, which will reduce the impact of materials' limitations.[1,2,12-16] Further, IOS impressions may potentially reduce the clinic time, enhance patient comfort, and allow for visualizing the adequacy of the impression immediately.[17-21] Over routine use, the IOS will minimize the material wastage and the ongoing costs. As the scanned model will remain virtual, physical models in many instances are not needed, which will reduce the need for a storage area.[19-21] On the other hand, the virtual model has the advantage of ease of transfer. Further, the generated virtual model can be magnified, which will facilitate the prosthesis design.[22] However, the IOS impressions require initial investment in scanning devices and they rely on clinician's skill to ensure adequate scanning. Therefore, for the IOS impression to be recommended for routine use, it should exhibit an accuracy that is, at least, similar to conventional impressions.[23-27] Recent review articles reported the capability of IOS systems to produce restorations of comparable accuracy to conventional methods.[28,29] However, to the knowledge of the authors, there is no detailed review article that focuses on the accuracy of the scanning phase and the influencing factors. Therefore, the aims of this systematic review are to evaluate the accuracy of IOS systems used in dentistry to scan teeth, and identify the factors that can influence the IOS accuracy.

MATERIALS AND METHODS

This systematic review was conducted according to the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)[30] (http://www.prisma-statement.org). The population, intervention, comparisons and outcomes (PICO) format were applied to define the search question. The PICO details were: population = tooth/teeth/arch; intervention = IOS technique(s); comparison = alternative impression technique(s); outcome = accuracy.

SEARCH METHODOLOGY

An electronic search of the literature was conducted mainly through PubMed (MEDLINE), Google Scholar, and Cochrane Central Registrar of Controlled Trials. The Boolean operator of the PubMed database was utilized to combine the following terms: ('intraoral' OR 'oral' OR 'tooth' OR 'teeth') AND ('scanner' OR 'scan' OR 'digitization' OR 'digital' OR 'impression') AND ('accuracy' OR 'precision') NOT ('implant'). The Google Scholar search engine was used to find additional articles by combining the following search terms 'intraoral', 'scanner', 'digitization', 'accuracy', and 'precision'. For the Cochrane Database, all the articles related to digital dentistry and CAD/CAM were retrieved. Additional databases (Scopus, EMBASE and Open Grey) were searched for possible articles. The titles of the articles were saved in reference software (EndNote, version X8.2, Thomson Reuters). The software was used to eliminate the duplicate articles from the different searches. The search aimed to collect all the articles that investigated the accuracy of IOS for teeth published until June 2017.

INCLUSION AND EXCLUSION CRITERIA

The study was considered for inclusion if it was published in a peer-reviewed journal, evaluating scanning accuracy, evaluating a current IOS system, on tooth scanning, clinical or laboratory study, and published in English language. The study was excluded if it was on implant component scanning or involved fit evaluation of restoration produced by computer-aided manufacturing *(Table 1)*.

Table 1. Inclusion criteria
Peer-reviewed publication
A study solely evaluating IOS accuracy, without computer-aided manufacturing
A study on a current IOS system
Study on tooth scanning
Not implant component scanning
Clinical or laboratory study
English language study

STUDY SELECTION

From the total literature pool, the selection of the final studies was executed in 3 stages: (1) study selection according to the title's relevance, (2) study selection according to abstract's contents, and (3) full-text analysis and matching against the inclusion criteria. The literature search was further supplemented by manual searching of the list of references of the included studies.

QUALITY ASSESSMENT

The Quality Assessment of Diagnostic Accuracy Studies (QUADAS) tool[31] was implemented to measure the risk of bias of the included studies. This was achieved by asking 14 questions *(Table 2)* for every study. For each question, a score of 1 was given if the answer was "yes". If the answer was "no" or "unclear", a score of 0 was given. Therefore, the highest possible score is 14, and the higher the score is indicative of lower risk of bias.

Table 2. Quality Assessment of Diagnostic Accuracy Studies (QUADAS) guidelines and scoring system

QUADAS questions	Score	
	Yes (1)	No/Clear (0)
Was the spectrum of arches/teeth representative of what will be diagnosed in practice?	( )	( )
Were the selection criteria clearly described?	( )	( )
Is the reference method likely to correctly classify the target condition?	( )	( )
Is the time period between reference method and test method short enough to be reasonably sure that the target condition did not change between the two tests?	( )	( )
Did the whole sample, or a random selection of the sample, receive verification using a reference standard of diagnosis?	( )	( )
Did the arches/teeth receive the same reference method regardless of the test method results?	( )	( )
Was the reference method independent of the test method (i.e. the test method did not form part of the reference standard)?	( )	( )
Was the execution of the test method described in sufficient detail to permit replication of the test?	( )	( )
Was the execution of the reference method described in sufficient detail to permit its replication?	( )	( )
Were the test method results interpreted without knowledge of the result of the reference method?	( )	( )
Were the reference method results interpreted without knowledge of the results of the test method?	( )	( )
Were the same clinical data available when test results were interpreted as would be available when the test is used in practice?	( )	( )
Were uninterpretable/intermediate test results reported?	( )	( )
Were withdrawals from the study explained?	( )	( )

OUTCOME VARIABLES

As some of the studies evaluated multiple features of IOS, only the data on accuracy were extracted. For each study, the following information were collected and summarized in Tables 4-6: author names, year of publication, sample number, IOS system(s), control impression(s), study set-up (clinical or laboratory), scanned substrate material, scanning span (partial arch or whole arch), evaluation method(s) and accuracy outcome. Due to the heterogeneity of the data, conducting a meta-analysis was not feasible. The accuracy of the IOS was evaluated by:

a) Dimensional measurement: Measuring the distance between landmarks on an IOS-generated virtual model and comparing it to the distance between similar landmarks an a physical model. The dimensional measurement evaluated the deviation from the conventional measurement of the physical model.

b) Superimposition accuracy: In this method, two virtual models are superimposed using the principles of best fit alignment. This is followed by quantifying the discrepancy between the models by 3D software. The less the value the greater the accuracy. This method was applied to measure 2 variables:

- Trueness: Comparing the IOS virtual model with the reference virtual model. The trueness measures the deviation from reference model.
- Precision: Comparing the similarity of virtual models generated by the same IOS system. The precision reflects the repeatability of the entire impression procedure.

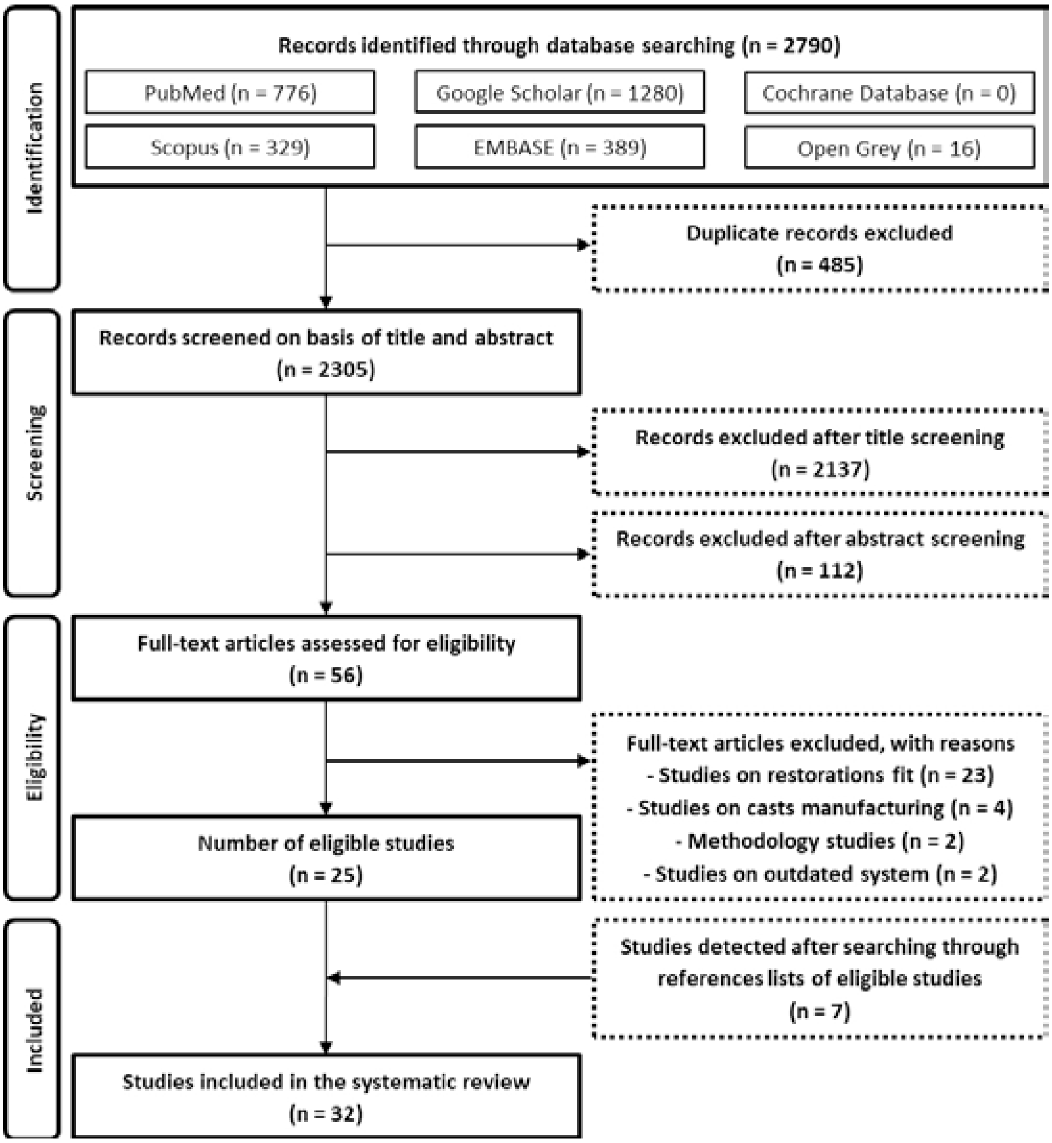

Figure 1: Flowchart of the literature search according to PRISMA guidelines

c) Qualitative evaluation: Following the superimposition process of 2 virtual models, a colour map is generated to illustrate the positive and negative differences between two virtual models. This method indicates the pattern of differences between the models produced from each IOS system.

RESULTS

LITERATURE SEARCH

A total of 2305 studies were obtained from the initial electronic search *(Figure 1)*. After reviewing the title relevance, 2137 studies were excluded which left 168 studies suitable for abstract screening. Analysis of the abstracts had led to the exclusion of additional 112 studies. Therefore, a total of 56 studies were analysed by full-text reading. After the implementation of the inclusion criteria, 25 studies were suitable for inclusion in the review. Searching through the references lists of the included studies had disclosed an additional 7 relevant studies. Therefore, this systematic review included a total of 32 studies.[2,3,19-21,32-58]

DESCRIPTION OF STUDIES

The evaluated IOS were summarized in Table 3. According to QUADAS guidelines, the studies' quality scores ranged from 8 to 12 (out of 14). The scanned surfaces were natural teeth, dental stone, metal, ceramic, and polymer. Some of the studies performed the scanning on prepared teeth, while others were on unprepared teeth. In addition, some studies evaluated the accuracy of IOS clinically, while others were laboratory investigations. The control groups were laboratory scanners or conventional impressions, followed by laboratory or high precision research scanners. The conventional impression materials were irreversible hydrocolloid (alginate), polyvinyl siloxane (PVS) or polyether. In addition, some studies included direct scanning of conventional impressions. For the purpose of uniformity, the included studies were divided into 3 groups: dimensional measurement studies, partial arch studies and whole arch studies.

Table 3. Details of all the investigated systems by the included studies

Scanner (abbreviation)	Manufacturing details	Scanning mode	Scanned surface treatment
Cerec Bluecam (CB)	Sirona, Bensheim, Germany	Snap image acquisition after visible blue light emission	Powder application
Cerec Omnicam (CO)	Sirona, Bensheim, Germany	Continuous imaging to generate 3D Natural coloured imaging	
Cadent iTero (IT)	Cadent Inc., Carstadt, New Jersey, United State	Snap image after laser emission based on confocal microscopy principles	
Lava C.O.S (LC)	3M ESPE, Seefeld, Germany	3D in-motion video imaging technology	Light powder application
Lava True Definition (LTD)	3M ESPE, Seefeld, Germany	3D in-motion video imaging technology	Light powder application
TRIOS (TS)	3Shape, Copenhagen, Denmark	Ultrafast imaging based on confocal microscopy principles	
TRIOS Color (TSC)	3Shape, Copenhagen, Denmark	Ultrafast imaging based on confocal microscopy principles Natural coloured imaging	
E4D (E4D)	D4D Technologies, LLC, Richardson, Texas, United State	High speed image acquisition after red light emission based on confocal microscopy principles	
Planscan (PS)	Planmeca, Richardson, Texas, United State	High speed image acquisition after blue laser emission based on confocal microscopy principles Natural coloured imaging	
MHT (MHT)	3D Progress, Verona, Italy	Real-time 3D image acquisition	
Carestream 3500 (CS)	Carestream Dental, Atlanta, Georgia, United State	Single image acquisition with the aid of light guidance Natural coloured imaging	
Zfx intrascan (ZFX)	Zfx GmbH, Dachau, Germany	Snap image based on confocal microscopy principles	

OUTCOME

Dimensional measurements studies

Five studies evaluated the accuracy of dimensional measurements on virtual models generated from IOS *(Table 4)*.[19-21,48,49] All of the studies were clinical and the evaluated systems were CO, IT, LC, LTD, TS and TSC. Three studies reported significant difference in the measured dimensions (distance and Bolton ratio) between IOS virtual models and casts generated from alginate impressions.[20,21,49] Likewise, Kuhr *et al* observed that polyether impressions exhibited less deviation for all the measured distances than IOS virtual models.[48] However, as the actual difference is minimal, the studies concluded that the differences were not of clinical significance. On the other hand, Grunheid *et al* found the measurements of tooth positions and arch dimensions were similar between IOS virtual models and alginate impressions.[19] Overall, the outcomes of these studies indicate that the IOS can be used reliably for treatment planning purposes.

Partial arch studies

A total of 14 studies evaluated the accuracy of IOS for partial arch scanning.[2,32-38,50-54,58] Thirteen studies were laboratory based,[2,32-37,50-54,58] and one of them was clinical *(Table 5)*.[38] The IOS systems were CB, CO, IT, LC, LTD, TS, E4D, MHT, CS, PS and ZFX.

Table 4. Dimensional measurements studies

Study (year)	Study quality score (0-14)	Impression methods	Sample description (material)	Sample size	Evaluation method	Accuracy
Clinical studies						
Naidu and Freer (2013)[21]	11	IOS: IT Control: Alginate impression poured in plaster	Whole arch (natural dentition)	30 per method (30 participants)	Measurement of tooth width and Bolton analysis	The digital casts were 24.0 µm larger on average than conventional casts
Wiranto et al (2013)[20]	11	IOS: LC Control: Alginate impression poured in plaster, and alginate impression scanned by laboratory scanner	Whole arch (natural dentition)	22 per method (22 participants)	Measurement of tooth width and Bolton analysis	Similar tooth width measurements for all the impression techniques The difference in Bolton analysis did not exceed 1.5 mm
Grunheid et al (2014)[19]	11	IOS: LC Control: Alginate impression scanned by laboratory scanner	Whole arch (natural dentition)	15 per method (15 participants)	Measurement of tooth positions differences at: -Vertical plane -Transverse plane -Sagittal plane Measurement of the arch dimension differences: -Width -Length	The average tooth position differences between the impressions were 20.0 µm for the maxillary teeth and 10.0 µm for the mandibular teeth The average differences in the arch width were 180.0 µm for the maxilla and 90.0 µm for the mandible The average differences in the arch length were 380.0 µm for the maxilla and 210.0 µm for the mandible
Kuhr et al (2016)[46]	11	IOS: CO, LTD and TS Control: Cast produced from polyether impression and scanned by coordinate measuring machine	Whole arch natural dentition with 4 metal spheres	50 per method (50 participants)	Measurement of linear distance between the centre of the spheres that correspond to: -Intercanine distance -Intermolar distance -Diagonal distances -Segment distances	The polyether impression had the lowest deviation for all the distances followed by LTD, TS and OC The intermolar distance had the greatest deviation CAN BE CONSIDERABLE REVIATION UP TO 0.8 mm
Camardella et al (2017)[47]	11	IOS: TSC Control: Alginate impression poured in plaster	Whole arch (natural dentition)	56 per model (28 participants)	Measurement of 52 distances including: -Tooth diameter -Tooth height -Overjet and overbite -Intercanine and intermolar distances -Sagittal relationship	For several parameters, statistical significant difference was observed. However, most of the differences were not considered clinically significant Maxillary central incisor height measurements had the greatest discrepancy

Table 5. Partial arch studies

Study (year)	Study quality score (0-14)	Impression methods	Sample description (material)	Sample size	Evaluation method	Accuracy
Laboratory studies						
Mehl et al (2009)[30]	9	IOS: CB	Single tooth prepared for inlay, partial crown or full crown (stone) Quadrant with inlay, crown or FPD preparation (stone)	17 single teeth 13 quadrants	Superimposition against 3D model obtained from reference scanner to measure trueness Qualitative evaluation	Single tooth trueness: 19.2 µm Quadrant trueness: 35.0 µm
Guth et al (2013)[2]	11	IOS: LC Control: Cast produced from polyether impression and scanned by laboratory scanner	4 unit FPD abutments (metal)	12 per method	Superimposition against 3D model obtained from reference scanner to measure trueness	LC trueness: 15.0 µm Polyether impression trueness: 36.0 µm
Nedelcu and Persson (2014)[31]	9	IOS: CB, IT, LC, and E4D	A model simulating single prepared tooth dimensions (PMMA, Ti and Zr)	10 per model and IOS	Superimposition against 3D model obtained from reference scanner to measure trueness Qualitative evaluation	CB trueness: -PMMA: 12.0 µm -Ti: 8.5 µm -Zr: 9.5 µm IT trueness: -PMMA: 15.5 µm -Ti: 9.5 µm -Zr: 7.0 µm LC trueness: -PMMA: 14.0 µm -Ti: 15.0 µm -Zr: 10.5 µm E4D trueness: -PMMA: 35.5 µm -Ti: 29.5 µm -ZR: 23.0 µm
Ali (2015)[32]	11	IOS: CB, IT, LC, and E4D Control: Scanning PVS impression by laboratory scanner	3 unit FPD abutments (epoxy resin)	5 per method	Superimposition against 3D model obtained from laboratory scanner to measure trueness	CB trueness: 68.0 µm IT trueness: 23.0 µm LC trueness: 36.0 µm E4D trueness: 84.0 µm Laboratory scanner trueness: 44.0 µm

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Table 5. Partial arch studies

Su and Sun (2015)[33]	11	IOS: TS Control: Laboratory scanner	Maxillary teeth model models (resin) with 5 arrangements of prepared teeth for crowns: -Central incisor -1st molar -3 unit anterior FPD -Half arch prepared teeth	10 per arrangement and method	Superimposition restricted to the prepared areas within the same group to measure precision	TS precision: -Central: 13.3 µm -Molar: 7.0 µm -Bridge: 16.3 µm -Half arch: 41.6 µm Laboratory scanner precision -Central: 14.9 µm -Molar: 8.7 µm -Bridge: 24.3 µm -Half arch: 14.2 µm
Yang et al (2015)[34]	12	IOS: TS, and MHT Control: Cast produced from PVS impression and scanned by 2 laboratory scanners (D700 and inEos)	Single prepared molar tooth for crown (natural tooth)	10 per method	Superimposition against 3D model obtained from micro-Ct scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	TS: -Precision: 7.6 µm -Trueness: 64.5 µm MHT: -Precision: 12.5 µm -Trueness: 61.9 µm D700 laboratory scanner: -Precision: 4.5 µm -Trueness: 66.7 µm inEos laboratory scanner: -Precision: 3.4 µm -Trueness: 71.2 µm
Guth et al (2016)[48]	11	IOS: CB, CO, LTD, CS and ZFX Control: Cast produced from polyether impression and scanned by laboratory scanner	4 unit FPD abutments (metal)	12 per method	Superimposition against 3D model obtained from reference scanner to measure trueness	CB trueness: 29.0 µm CO trueness: 31.0 µm LTD trueness: 11.0 µm CS trueness: 14.0 µm ZFX trueness: 33.0 µm Laboratory scanner trueness: 19.0 µm
Kim et al (2016)[49]	8	IOS: CO, TS and CS	Mandibular quadrant model (resin) with 4 prepared teeth, and 2 arrangements: -With edentulous area -With alumina landmark on the middle of the edentulous area	5 per arrangement and method	Superimposition restricted to the prepared teeth areas against 3D model obtained from reference scanner to measure trueness Superimposition restricted to the prepared teeth areas within the same group to measure precision	CO: -Trueness with marker: 31.8 µm -Precision with marker: 10.5 µm TS: -Trueness with no marker: 36.1 µm -Trueness with marker: 30.6 µm -Precision with no marker: 13.0 µm -Precision with marker: 9.2 µm CS: -Trueness with no marker: 38.8 µm -Trueness with marker: 26.7 µm -Precision with no marker: 43.6 µm -Precision with marker: 12.4 µm

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Table 5. Partial arch studies

Renne et al (2016)[50]	11	IOS: CB, CO, IT, TS, PS and CS Control: Laboratory scanner	Maxillary sextant on unprepared posterior teeth (PMMA)	5 per method	Superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision	CB: -Trueness: 57.5 μm -Precision: 89.6 μm CO: -Trueness: 56.2 μm -Precision: 89.8 μm IT: -Trueness: 57.4 μm -Precision: 84.6 μm TS: -Trueness: 68.8 μm -Precision: 98.0 μm PS: -Trueness: 48.4 μm -Precision: 79.8 μm CS: -Trueness: 68.6 μm -Precision: 97.0 μm Laboratory scanner -Trueness: 49.9 μm -Precision: 79.0 μm
Rudolph et al (2016)[35]	12	IOS: CB, IT, LC, and TS Control: Cast produced from polyether impression and scanned by 10 different laboratory scanners (es1, Everest Scan Pro, Lava Scan, Lava Scan ST, ZENO Scan S100, D250, D640, digiSCAN and S900)	Single prepared incisor and molar (zr)	10 per method	Superimposition against 3D model obtained from reference scanner to measure trueness Qualitative evaluation	CB trueness: 14.4 μm IT trueness: 10.7 μm LC trueness: 8.0 μm TS trueness: 6.4 μm es1 laboratory scanner trueness: 7.9 μm Everest Scan Pro laboratory scanner trueness: 8.6 μm Lava Scan laboratory scanner trueness: 9.4 μm Lava Scan ST laboratory scanner trueness: 11.1 μm ZENO Scan S100 laboratory scanner trueness: 12.1 μm D640 trueness: 12.2 μm D250 trueness: 18.9 μm digiSCAN laboratory scanner trueness: 13.7 μm digiSCAN laboratory scanner (with zoom lens) trueness: 29.4 μm Scan 900 laboratory scanner trueness: 33.4 μm

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Table 5. Partial arch studies

Carbajal Mejia et al (2017)[56]	12	IOS: TS Control: Cast produced from PVS impression and scanned by laboratory scanner	Single prepared incisors with different TOC: -8, -6, -4, 0, 4, 6, 8, 12, 16 and 22º (PMMA)	5 per preparation and method	Superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	TS: -Trueness: 19.1 µm -Precision: 11.9 µm Laboratory scanner -Trueness: 23.5 µm -Precision: 20.7 µm
Lee et al (2017)[51]	12	IOS: CB and CO Control: Cast produced from PVS impression and scanned by laboratory scanner, and direct scanning by laboratory scanner	Single prepared molar tooth for crown (PMMA)	6 per method	Superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	CB: -Trueness: 17.5 µm -Precision 12.7 µm CO: -Trueness: 13.8 µm -Precision: 12.5 µm Cast laboratory scanning: -Trueness: 17.4 µm -Precision: 9.2 µm Direct laboratory scanning: -Trueness: 12.3 µm -Precision: 6.9 µm
Uhm et al (2017)[52]	11	IOS: CB, CO, TS and CS Control: Laboratory scanner	Models simulating onlay preparation and 4 unit FPD abutments (metal)	30 per method	Superimposition against 3D model obtained from coordinate measuring maching to measure trueness Superimposition within the same group to measure precision	CB: -Inlay trueness: 71.8 µm -Inlay precision: 60.5 µm -FPD trueness: 166.3 µm -FPD precision: 136.5 µm CO: -Inlay trueness: 70.2 µm -Inlay precision: 53.0 µm -FPD trueness: 118.2 µm -FPD precision: 100.9 µm TS: -Inlay trueness: 51.9 µm -Inlay precision: 31.0 µm -FPD trueness: 129.8 µm -FPD precision: 112.2 µm CS: -Inlay trueness: 40.8 µm -Inlay precision: 36.0 µm -FPD trueness: 154.2 µm -FPD precision: 77.1 µm Laboratory scanner: -Inlay trueness: 7.6 µm -Inlay precision: 5.3 µm -FPD trueness: 55.6 µm -FPD precision: 12.1 µm

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Table 5. Partial arch studies

Clinical studies						
Ender et al (2015)[36]	12	IOS: CB, CO, IT, LC, LTD, TS, and TSC Control: Cast produced from full arch PVS impression and scanned by reference scanner, and cast produced from triple tray PVS impression and scanned by reference scanner	Maxillary or mandibular quadrant (natural dentition)	15 per method (5 participants)	Superimposition within the same group to measure precision Qualitative evaluation	CB precision: 34.2 µm CO precision: 43.3 µm IT precision: 49.0 µm LC precision: 47.7 µm LTD precision: 21.8 µm TS precision: 25.7 µm TSC precision: 26.1 µm Full arch PVS impression precision: 18.8 µm Triple tray PVS impression precision: 58.5 µm

IOS vs Conventional methods: For single tooth scanning, several studies found the IOS systems exhibited similar accuracy to casts produced from PVS and polyether impressions.[36,37,53] On the other hand, Carbajal Mejia *et al* found IOS (TS) is more accurate than casts produced from PVS for single prepared incisors.[58] However, Yang *et al* reported the IOS were more vulnerable to deviation at the marginal area than conventional impressions.[36] For 3-unit FPD abutments, Ali found some IOS systems (IT and LC) had no significant difference in trueness with laboratory scanning of PVS impressions. Other IOS systems (CB and E4D), however, were inferior to the PVS impression.[34] Guth *et al* found that IOS generated models of greater trueness than casts produced by polyether impressions for 4-unit FPD abutments scanning.[2] In a more recent study, the same group evaluated the trueness of 5 different IOS systems against the same control group. They found the control group had inferior precision than some IOS (LTD and CS) systems and superior precision to other systems (CB, CO and ZFX).[50] The clinical study by Ender *et al* had found that the digital scanning of quadrant had a level of precision comparable to casts produced from conventional impression by partial tray with PVS.[38] However, all of the techniques were inferior to casts produced from conventional full arch PVS.[38] They also found that the accuracy of the conventional impressions deteriorated in areas of thin impression material, such as the occlusal area of triple tray.[38] Therefore, for single tooth and short-span scanning of up to 4 units, the IOS systems are comparable to conventional impressions.

Different IOS systems: Overall, the studies reported variable accuracy outcome for the different IOS systems. Nedelcu and Persson evaluated the accuracy of 4 IOS systems (CB, IT, LC and E4D) for single tooth scanning, and they reported variation in trueness.[33] In general, a similar accuracy was found for LC, CB and IT, which was greater than E4D. Further, the scanned substrate was found to influence the outcome, where zirconia scanning tended to be more accurate followed by titanium and PMMA respectively. The non-coating scanners had maximal deviation and they were more susceptible to alterations of scanned surfaces.[33] In another single ceramic tooth scanning study, LC and TS had greater accuracy than CB and IT.[37] Another study reported similar precision and trueness of TS and MHT for single molar scanning.[36] After comparing the accuracy of CB and CO for single tooth scanning, Lee *et al* reported similar precision for the two scanners.[53] However, the CB had slightly superior trueness than CO. For 3-unit FPD abutments scanning, Ali observed differences in trueness between the different scanners (CB, IT, LC and E4D). The most accurate systems were IT and LC, and the least accuracy was reported for E4D followed by CB.[34] For 4-unit FPD metal abutments scanning, Guth *et al* reported that the best trueness was associated with LTD followed by CS, CB, CO and ZFX respectively.[50] They attributed their results to the positive effect of powder coating for metal scanning. After resin sextant scanning, the trueness and precision of CS and TS were generally inferior to CB, CO, IT and PS.[52] Another study reported similar trueness for CO, TS and CS[51] for resin quadrant scanning. However, the precision was more affected by the different IOS. Uhm *et al* evaluated the accuracy of 4 IOS systems (CB, CO, TS and CS) for inlay and 4-unit FPD abutments.[54] For inlays scanning, while all of the systems had similar trueness, the TS and CS had the highest precision. On the other hand, for 4-unit FPD scanning, CO had the best trueness and the CS had the best precision.[54] For a quadrant impression, the clinical study by Ender *et al* had reported that CB, LTD, TS and TSC were similar, and had better precision than CO, IT and LC.[38] The qualitative evaluation revealed that the virtual image quality was influenced by the scanned site, morphology and surface. For example, steep areas, proximal and gingival areas were associated with greater inaccuracies.[38]

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Span effect: Overall, there is pattern of reduction of trueness and precision as the scanning span increases Mehl *et al* found that single tooth scanning (CB) was more accurate than quadrant scanning.[32] Similarly Su and Sun reported a reduction of scanning (TS) precision as the span increased.[35] For single central incisor tooth preparation, the precision was similar for the IOS and laboratory scanner. However, for single molar preparation, 3-unit FPD abutments and half arch scanning, the laboratory scanner produced a more precise outcome. The authors concluded the IOS has acceptable accuracy if the scanning scope is less than half the arch. Another study found that the trueness and precision of inlay scans were consistently superior to the trueness and precision of 4-unit FPD abutments scans.[54] In the same study, the laboratory scanner was less affected by the span. After scanning a mandibular quadrant with an edentulous area equivalent to 3 missing teeth, Kim *et al* reported significant improvement of trueness and precision of TS and CS after placement of alumina marker in the middle of the edentulous area.[51]

Tooth category and morphology: Three studies evaluated the effect of tooth category and morphology on accuracy.[35,37,58] One study found that the molar preparation tended to be insignificantly more accurate than incisor preparation scanning.[35] The other study found single incisor preparations had greater deviation than molars.[37] This was attributed to the steeper surfaces of the incisors as opposed to molars. One study evaluated the effect of altering the total occlusal convergence angle (TOC) of maxillary central incisor.[58] They reported that IOS is efficient in accurately recording the prepared tooth regardless of the TOC, while the PVS impression accuracy deteriorated with TOC of less than 8^{o}. They attributed this outcome to the vulnerability of PVS material to distortion after removal from areas with great parallelism or undercuts.

Whole arch studies

A total of 16 studies evaluated the accuracy of IOS for whole arch scanning. Eleven studies were laboratory based,[3,35,39-45,52,55] and 5 studies were clinical studies *(Table 6)*.[46-48,56,57] The IOS systems were CB, CO, IT, LC, LTD, TS, TSC, PS and CS.

IOS vs Conventional methods: Ender and Mehl reported similarity in precision and trueness between 2 IOS systems (CB and LC) and polyether impression.[39] In another study, Ender and Mehl found the PVS exhibited greater precision and trueness than the CB.[3] In a more recent study, the same researchers compared 4 IOS systems (CB, CO, IT and LC) against casts produced by PVS, polyether and alginate impressions. In addition, they included PVS impression scanned by laboratory scanner.[42] The PVS casts were the most accurate amongst all of them. The alginate impressions produced casts with comparable trueness and precision to CO, LC and IT,[42] while, the CB was more accurate. However, the polyether impression suffered from the greatest deviation and least precision.[42] Scanning PVS impressions by laboratory scanner produced inferior outcomes than PVS cast, but comparable to IOS systems. In a clinical study, Ender *et al* compared the precision of multiple IOS systems with similar conventional group to their earlier study.[38] All the IOS systems were inferior to the conventional impressions except for the alginate. The highest precision was for PVS cast and scanned PVS impression, followed by polyether impression. Jeong *et al* compared the precision and trueness of two IOS systems (CB and CO) against PVS impression. The PVS impression was more precise than the two IOS systems. However for trueness, the CO and PVS were similar and significantly better than CB.[44] Similarly, greater trueness and precision were observed for PVS cast over CO by another study.[57] A clinical study by Flugge *et al* compared the precision of IT with polyether casts. In addition, the casts were scanned by the IOS and laboratory scanner. They reported significant differences between the groups, where the intraoral use of IT was most inferior, followed by scanning the cast with IT. The laboratory scanning of polyether casts was the most accurate.[46] Similarly, Kuhr *et al* reported that casts produced from polyether impressions had the best trueness and least deviation in comparison to IOS.[48] The qualitative evaluation revealed that the different impression techniques were associated with different patterns of distortion. The most clear deviation pattern for IOS was the distortion at the most posterior region of the arch.[3,44,46,57] Further, the anterior segment of the arch was more accurate than posterior segments for the IOS-generated models.[3] Overall, the IOS systems were more vulnerable to deviation than conventional methods.[42,46,57] The IOS accuracy was found to be influenced by the tooth morphology, where sharp edges and proximal areas had negatively influenced the accuracy.[46,47] On the other hand, the laboratory scanner was less affected by the location and the morphology of the teeth.[46] The PVS generally had minimal deviations, while the alginate and polyether impressions had more localized deviations.[47]

Different IOS systems: Considerable variation between the studies was observed. Similar to partial arch studies, no consistent pattern was observed after comparing the outcome of the whole arch studies. Ender and Mehl had found CB and LC did not differ in the trueness while for the precision; the CB had a superior outcome.[39] In another study, the same authors confirmed the CB is significantly more accurate than CO, IT and LC.[42] The other scanners were similar statistically. Patzelt *et al* evaluated the trueness and precision of CB, IT, LC and MHT on prepared teeth. All of them had comparable accuracy except for the CB which had notable inferior trueness.[41] In the same study, the qualitative evaluation found that the most posterior region suffered from the greatest distortion. In the clinical study by Ender *et al*, most of the evaluated IOS systems (CB, CO, IT, LC, LTD, TS and TSC) were similar except for the LC which had inferior precision.[47] One study found that the TS is able to provide a slightly more consistent outcome than IT.[43] Renne *et al* evaluated the accuracy of 6 IOS systems. They found IT had the highest trueness and precision followed by TS, CS, PS, CO and CB respectively.[52] Another study found that the LTD had slightly higher trueness than TS and significantly higher trueness than CO.[48] Rehmann *et al* found recently calibrated CB had the highest trueness followed by IT and LC.[55] Interestingly, the same study reported a significantly positive effect of manufacturer calibration on the trueness of CB and LC.

Table 6. Whole arch studies

Study (year)	Study quality score (0-14)	Impression methods	Sample description (material)	Sample size	Evaluation method	Accuracy
Laboratory studies						
Ender and Mehl (2011)[37]	12	IOS: CB, and LC Control: Cast produced from polyether impression and scanned by reference scanner	Whole arch with 3 prepared teeth (metal)	5 per method	Superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	CB: -Trueness: 49.0 µm -Precision: 30.9 µm LC: -Trueness: 40.3 µm -Precision: 60.1 µm Polyether impression: -Trueness: 55 µm -Precision: 61.3 µm
Ender and Mehl (2013)[3]	12	IOS: CB Control: Cast produced from PVS impression and scanned by reference scanner	Whole arch with 3 prepared teeth (metal)	5 per method	Superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	CB: -Trueness: 58.0 µm -Precision: 32.4 µm PVS impression: -Trueness: 20.4 µm -Precision: 12.5 µm
Ender and Mehl (2013)[38]	9	IOS: CB with 3 different scanning strategies (occlusal, diagonal, and rotational), LC with 2 different scanning strategies (occlusal, buccal and lingual along the arch, and rotational around each tooth), and IT	Whole arch with 3 prepared teeth (metal)	5 per method	Superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	CB occlusal scanning -Trueness: 52.5 µm -Precision: 32.4 µm CB diagonal scanning -Trueness: 29.4 µm -Precision: 19.5 µm CB rotational scanning -Trueness: 23.3 µm -Precision: 23.9 µm IT: -Trueness: 35.0 µm -Precision: 30.9 µm LC rotational scanning: -Trueness: 90.2 µm -Precision: 43.2 µm LC occlusal, buccal and lingual scanning -Trueness: 45.8 µm -Precision: 45.2 µm

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Table 6. Whole arch studies

Patzelt et al (2014)[39]	9	IOS: CB, IT, LC and MHT	Whole arch of 14 prepared teeth (polyurethane)	5 per IOS	Superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	CB: -Trueness: 332.9 µm -Precision: 99.1 µm IT: -Trueness: 49.6 µm -Precision: 40.5 µm LC: -Trueness: 38.0 µm -Precision: 37.9 µm MHT: -Trueness: 73.7 µm -Precision: 90.2 µm
Ender and Mehl (2015)[40]	12	IOS: CB, CO, IT, and LC Control: Casts produced from alginate, polyether or PVS impression and scanned by reference scanner, and PVS impression scanned by laboratory scanner	Whole arch with 3 prepared teeth (metal)	5 per method	Superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	CB: -Trueness: 29.4 µm -Precision: 19.5 µm CO: -Trueness: 37.3 µm -Precision: 35.5 µm IT: -Trueness: 32.4 µm -Precision: 36.4 µm LC: -Trueness: 44.9 µm -Precision: 63.0 µm Polyether impression: -Trueness: 60.2 µm -Precision: 66.7 µm PVS impression: -Trueness: 13.0 µm -Precision: 12.3 µm PVS impression scanning: -Trueness: 35.1 µm -Precision: 39.6 µm Alginate impression: -Trueness: 37.7 µm -Precision: 59.6 µm
Su and Sun (2015)[33]	11	IOS: TS Control: Laboratory scanner	Whole arch of 14 prepared teeth (polyurethane)	10 per arrangement and method	Superimposition restricted to the prepared areas within the group to measure precision	TS precision: 88.4 µm Laboratory scanner precision: 12.7 µm

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...table 6 continued

Table 6. Whole arch studies

Anh et al (2016)[41]	9	IOS: IT with 2 different scanning strategies that start on the occlusal surface followed by buccal and lingual surfaces (right posterior teeth till anterior teeth followed by the left side, and reversing the scanning sequence), and TS with 2 different scanning sequences that start on the occlusal surface followed by buccal and lingual surfaces (right posterior teeth till the left posterior teeth, and reversing the scanning sequence)	Whole maxillary arch of unprepared teeth (resin) with different degrees of crowding: -Arch 1: ideal arch -Arch2: mild crowding -Arch 3: moderate crowding -Arch 4: severe crowding	6 per arrangement and method	Superimposition within the same group to measure precision Qualitative evaluation	IT: -Arch 1: 28.2 µm -Arch 2: 29.6 µm -Arch 3: 28.4 µm -Arch 4: 33.2 µm TS: -Arch 1: 23.8 µm -Arch 2: 21.9 µm -Arch 3: 21.0 µm -Arch 4: 22.0 µm
Jeong et al (2016)[42]	12	IOS: CB, and CO Control: Cast produced from PVS impression and scanned by laboratory scanner	Whole maxillary arch of unprepared teeth (resin)	8 per method	Superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	CB: -Trueness: 378.0 µm -Precision: 116.0 µm CO: -Trueness: 197.0 µm -Precision: 58.0 µm Laboratory scanner: -Trueness: 170 µm -Precision: 78.0 µm
Muller et al (2016)[43]	9	IOS: TS with 3 different scanning strategies (buccal-occlusal surface of the whole arch followed by occlusal-palatal surface, occlusal-palatal surface of the whole arch followed by buccal-occlusal surface, and alternating between the buccal, occlusal and palatal surface of each tooth and moving along the arch)	Whole arch with 3 prepared teeth (metal)	5 per scanning strategy	Superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	Buccal-occlusal then occlusal-palatal scanning strategy: -Trueness: 17.9 µm -Precision: 35.0 µm Occlusal-palatal then buccal-occlusal scanning strategy: -Trueness: 17.5 µm -Precision: 7.9 µm Alternation between buccal, occlusal and palatal surface scanning strategy: -Trueness: 26.8 µm -Precision: 8.5 µm

table 6 continued overleaf...

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Table 6. Whole arch studies

Renne et al (2016)[50]	11	IOS: CB, CO, IT, TS, PS and CS Control: Laboratory scanner	Whole maxillary arch of unprepared teeth (PMMA)	5 per method	Superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision	CB: -Trueness: 140.5 μm -Precision: 194.2 μm CO: -Trueness: 101.5 μm -Precision: 133.4 μm IT: -Trueness: 56.2 μm -Precision: 89.4 μm TS: -Trueness: 69.4 μm -Precision: 105.6 μm PS: -Trueness: 96.2 μm -Precision: 124.6 μm CS: -Trueness: 76.0 μm -Precision: 113.8 μm Laboratory scanner -Trueness: 43.6 μm -Precision: 105.6 μm
Rehmann et al (2017)[53]	8	IOS: CB (decalibrated), CB (calibrated), LC (decalibrated), LC (calibrated), IT	Whole arch with 3 prepared teeth (metal)	10 per method	Superimposition against 3D model obtained from reference scanner to measure trueness	CB (decalibrated) trueness: 108.4 μm CB (calibrated) trueness: 16.5 μm LC (decalibrated) trueness: 80.9 μm LC (calibrated) trueness: 34.9 μm IT trueness: 24.4 μm
Clinical studies						
Flugge et al (2013)[44]	12	IOS: IT Control: Cast produced from polyether impression and scanned by laboratory scanner and IOS (IT)	Whole arch (natural dentition)	10 per method (1 participant)	Superimposition within the same group to measure precision Qualitative evaluation	IT precision: 50.0 μm Polyether impression precision (laboratory scanner): 10.0 μm Polyether impression (IOS) precision: 25.0 μm
Ender et al (2015)[45]	12	IOS: CB, CO, IT, LC, LTD. TS, and TSC Control: Casts produced from alginate, polyether or PVS impression and scanned by reference scanner, and PVS impression scanned by laboratory scanner	Whole arch (natural dentition)	15 per method (5 participants)	Superimposition within the same group to measure precision Qualitative evaluation	CB precision: 56.4 μm CO precision: 48.6 μm IT precision: 68.1 μm LC precision: 82.8 μm LTD precision: 59.7 μm TS precision: 47.5 μm TSC precision: 42.9 μm PVS impression precision: 17.7 μm Scanned PVS impression: 18.3 μm Polyether impression precision: 34.9 μm Alginate impression precision: 162.2 μm

table 6 continued overleaf...

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Table 6. Whole arch studies

Gan et al (2016)[54]	9	IOS: TS	Whole arch (natural dentition) with different palatal vault height (low, medium and high) and width (narrow, medium and wide)	96 per method (32 participants)	Superimposition against 3D model obtained from conventional impression and laboratory scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	TS: -Narrow arch trueness: 74.2 µm -Narrow arch precision: 53.9 µm -Medium arch trueness: 80.6 µm -Medium arch precision: 57.6 µm -Wide arch trueness: 85.1 µm -Wide arch precision: 67.4 µm
Kuhr et al (2016)[46]	11	IOS: CO, LTD and TS Control: Cast produced from polyether impression and scanned by coordinate measuring machine	Whole arch (natural dentition) with 4 metal spheres	50 per method (50 participants)	Virtual spheres superimposition against reference spheres CAD image to measure trueness	CO trueness: 214 µm LTD trueness: 23.0 µm TS trueness: 37.0 µm Polyether impression trueness: 15.0 µm
Atieh et al (2017)[55]	12	IOS: CO Control: Cast produced from PVS impression and scanned by reference scanner	Whole arch (natural dentition) with metal appliance	5 per method (5 participants)	Virtual appliance superimposition against 3D model obtained from reference scanner to measure trueness Superimposition within the same group to measure precision Qualitative evaluation	CO: -Trueness: 46.2 µm -Precision: 61.1 µm PVS impression: -Trueness: 17.0 µm -Precision: 16.9 µm

Span effect: Only two studies compared the whole arch scanning to shorter span scanning.[35,52] Su and Sun found that scanning the whole arch by TS is associated with half the trueness of half arch scanning.[35] Similarly, Renne *et al* reported that scanning a whole arch was associated with less trueness and precision than sextant scanning.[52] The least affected IOS systems with the increase of the span were IT, TS and CS. The two studies confirmed that laboratory scanning was less influenced by the span of the scanning.

Scanning strategy: A total of 3 studies evaluated the effect of scanning strategy on the accuracy.[40,43,45] Ender and Mehl investigated the effect of different scanning strategies for CB and LC. For the CB, the diagonal and rotational scanner camera orientations were superior to the occlusal orientation. For the LC, the precision was the same for straight occlusal, buccal and lingual scanning and rotational scanning around each tooth. However, the straight scanning had superior trueness.[40] Anh *et al* evaluated different scanning sequences for IT and TS. For each scanner, one scanning sequence started on the right, and the other sequence started on the left. Although the difference between the different scanning sequences was statistically significant, the actual difference was minimal. The IT was more influenced from changing the sequence.[43] The study by Muller *et al* compared trueness and precision of 3 scanning strategies for TS: buccal-occlusal surface of the whole arch followed by scanning the palatal surface, occlusal-palatal surface of the whole arch followed by scanning the buccal surface, and alternation or rotation between the buccal and palatal surface. They found the second scanning strategy to have the greatest precision and trueness. However, the significant difference was observed for precision only.[45] Regardless of the scanning strategy, the most posterior region suffered from the greatest distortion.[40,43,45]

Teeth arrangements: One paper included dental models of different crowding conditions: ideal, mild, moderate and severe crowding conditions.[43] The study found the crowding

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status of the arch did not influence the accuracy of the virtual model obtained from IT and TS. In a severely crowded arch, the proximal areas suffered from greater deficiency. Another study evaluated the impact of arch width (narrow, medium and wide) on the trueness and precision of TS.[56] Overall, there was tendency for the trueness and precision to reduce as the arch width increases. However, significant difference existed only for precision.

DISCUSSION

This systematic review indicates that regardless of the impression technique, the material and the system used, there is an inevitable form of inaccuracy. In addition, it is clear that the included studies had considerable heterogeneity in terms of evaluation methods, systems evaluated and control groups. This reflects on the conflicting outcomes of the studies. As a result, conducting a meta-analysis was not feasible. Although several systematic reviews were published on the topic of IOS, the present review is unique in identifying the factors that may influence IOS accuracy.

IOS VS CONVENTIONAL METHODS

Since conventional impressions are the benchmark for the comparison, they are used by several studies as control methods against IOS systems. It is also known that, through the conventional impression procedure, every material and step will contribute to the final discrepancy. This involves the impression material setting, impression removal and stone material setting.[38,42,47] Earlier reports indicated that alginate exhibits the least accuracy of the conventional impressions materials, while PVS is the most accurate.[6,7] As a result, alginate impression is commonly used to obtain diagnostic models. Since the accuracy of IOS systems were found to be similar or superior to alginate impression accuracy,[2,19-21,38,39,42] it can be assumed that the IOS impression can be safely used for diagnostic purposes. Due to the higher accuracy of PVS and polyether impression materials, they are used to produce working casts for prosthesis fabrication. Overall, there is tendency for the studies of this systematic review to support the superior accuracy of PVS and polyether impressions over IOS impression. However, this observation appears to be dependent on the span of the impression. For single tooth scanning, the available evidences indicate similarity in the accuracy of IOS impression, PVS impression[36,53] and polyether impression.[37] For short span FPD abutments impression, the IOS is still comparable to PVS and polyether impressions.[2,34,50] As soon as the span increases to cover the entire quadrant, the superiority of PVS impression becomes more apparent.[38] For whole arch scanning, the studies consistently revealed the superiority of PVS impression over IOS impression.[3,38,42,44] The polyether impression still appears to be inferior to PVS impression and in some studies it is superior to IOS,[38,46,48] while for other it is similar or inferior to IOS.[39,42] Nevertheless, although statistical differences were observed between IOS and conventional impressions, the clinical significance of this dimensional difference is yet to be determined.

The inaccuracy associated with IOS impressions can be related to the steps involved with the scanning procedure. Any light scanning process is based on emitting light on tooth surface and capturing the reflected light. Excessive reflection, due to metallic restoration or excessive saliva, or areas with poor access, will influence the quality and the sharpness of the captured image.[4,5,33] Further, light obstruction will cause shadowing and loss of the entire shadowed area. Several included studies had found that areas associated with shadowing (steep surfaces, sharp edges, proximal areas and gingival margins) were more likely to suffer from greater discrepancies.[32,37,38,46,47] For example, 2 studies had found that IOS impressions of posterior teeth tended to be more accurate than anterior teeth, which can be attributed to the reduced preparation height and inclination for posterior teeth.[35,37] Due to the influence of the scanned surface on scanner accuracy, light scanning has been found to be associated with significant surface noise.[25] Although the surface noise is eliminated by software filtering, the process can cause rounding of sharp edges, and loss of surface details. As IOS cannot capture the whole arch with a single scan, multiple overlapping scans have to be taken and combined via stitching algorithm. As a consequence, every stitching process can introduce additional discrepancy. Eventually, the error will be propagated for every stitching process.[46,47] This explains the observation of many included studies, that the inaccuracy increases as the span of the scanning increases.[3,40-42,44,45,47,48] This becomes more obvious at the terminal end of the arch (molars region). In addition, the presence of long span edentulous area negatively influenced the accuracy of IOS.[51] This can be attributed to the lack of defined and stable intraoral features that can ensure rigid stitching. The other drawback feature of the IOS process is the vulnerability to patient factors, such as the presence of saliva, the patient's and operator's movements, access in the mouth and soft tissue stability.[32,46]

On the other hand, conventional impression and laboratory scanning do not require numerous stitching as opposed to IOS scanning; thus can potentially be more accurate. Further, each image obtained from the laboratory scanner covers the whole arch, which means recording the whole arch dimension in every scan shot.[3,35,42,47,52] Although stitching is applied for laboratory scanners, it is automated and involves a larger overlap field that covers the whole arch length. As a result, the whole arch distortion is less significant than for IOS systems.[35,52]

EFFECT OF IOS SYSTEM

Overall, this review indicates that while all the IOS systems are capable of generating virtual models of acceptable accuracy in certain applications, they share similar limitations. However, different studies have reported variable outcomes from the different IOS systems. Therefore, from this systematic review, no recommendations can be made on which system is most superior. This difference can be attributed to the studies' methodology, operator's familiarity with the system, learning curve associated with using these systems, ergonomic design of the handheld cameras, and IOS calibration.[16,34,37-43,45,47,55] In addition, some studies scanned prepared teeth, while others scanned intact teeth, which may be more difficult to scan due to the presence of undercuts, steep surfaces, inclinations and occlusal anatomy. Further, some of the studies were laboratory based and others were clinical, which poses extra challenges on the IOS. Part of the differences in the outcomes can be related to the systems continuously undergoing hardware and software updates to improve performance. Interestingly, one study reported significant reduction of accuracy if the IOS systems were not routinely calibrated.[55] Due to the considerable variation in the methodology and the outcome of the included studies, it is necessary to establish universally accepted and standardized method for IOS accuracy evaluation.

For prepared metal abutment scanning, some studies indicated that systems using powder coating provided more accurate and consistent outcomes after scanning different substrates.[33,50] This may be due to enhancing the reflection of the emitted light from the scanned surface. It has been speculated that emitted light on surface with no powder is prone to refraction and scattering, which may result in a deficient determination of the depth of the scanned object.[18] As a result, image error can occur if the tooth has a restoration with different reflective and refractive properties than natural tooth. On the other hand, no superiority of powdered scanning was obvious by several studies.[34,38,41,42,44,47,48,52,53] Therefore, currently, the effect of powder application on the surface is not very clear. However, in a clinical situation, powder application and maintenance with the presence of saliva is more challenging,[38,47] and the clinician should consider the length of the scanning span and the difficulties in maintaining an even powder layer through the duration of long span scanning.

The magnitude of discrepancy between the studies was variable, and some whole arch studies had found a considerable average deviation of the whole virtual model (100 µm or more). While this amount of deviation may not necessary lead to poorly fitting prostheses on each individual tooth, such discrepancy magnitudes will lead to inaccurate articulation of the maxillary and mandibular virtual casts. Thus, as the complexity of the prosthesis increases, the discrepancy of occlusal and proximal contacts will also increase. In addition, not all definitive prostheses will be produced solely by chairside CAD/CAM systems. The digital streams of many systems involve fabrication of prosthesis coping that still require manual ceramic application. In order for the technician to apply the ceramic layer, the digital system will fabricate a physical cast on which the coping will fit. Currently, the physical cast can be fabricated by milling or printing, which will inevitably add to the accumulated distortion,[9] and has been shown to influence articulation.[26,27] In addition, the reported discrepancies of this review are only the inaccuracies associated with the first step of prosthesis fabrication via IOS, and further inaccuracies will be introduced at other stages, such as processing digital images, digital margin determination, virtual prosthesis design, and applying ceramic. To date, there are clinical studies confirming the suitability of using IOS for fabrication of single unit prosthesis,[10,11] however, longer span prostheses require further clinical validation.

It appears that there is an influence of the scanning sequence and camera movement on the accuracy of the virtual model. Clear recommendations with the current level of evidences are difficult due to the limited number of studies. Diagonal orientations or rotating the CB camera was found to be more accurate than occlusal orientation[40] which can be attributed to greater recording of overlapping areas and prominent features. Other systems (LC and TS) had benefited from recording the occlusal surface along the whole arch followed by the buccal and palatal surfaces respectively.[40,43] On the contrary, rotating the camera around each tooth along the arch, or recording half the arch one side, followed by the other side, were associated with greater deviations.[40,43] Registering the whole arch dimension from each scanning step appears to be advantageous as it reduces the systematic deviation from stitching of the images. In accordance with the earlier studies, Muller *et al* had found that recording the occlusal surface of the whole arch, followed by palatal and buccal surfaces respectively, was superior to scanning the buccal surface, followed by occlusal and palatal or rotating the camera around each tooth.[45] In addition, the investigation by Muller *et al* indicated that the commencement of the palatal surfaces is associated with greater accuracy due to the presence of more defined anatomy and rigid overlapping.[45] On the other hand, flat surfaces, such as the labial surface, may reduce the reliability of overlapping. Therefore, from the limited evidences, it can be speculated that scanning accuracy can be enhanced by reducing the reliance on software stitching of multiple scanned images. This can be accomplished by increasing the amount of overlapping areas, registering the span of the arch at the early stages of scanning, and commencement at the surfaces with more defined anatomical morphology.

CLINICAL RECOMMENDATIONS

From the previous discussion and the conflicting outcome of the studies, the scanning systems, scanner acquisition process and powder application do not appear to be major influencing factors on the accuracy of IOS. The included studies revealed multiple variables that can influence the accuracy of IOS, such as span length, scanning sequence and scanned surface morphology. While IOS can be safely used to acquire diagnostic models and treatment planning purposes, some recommendations are required for definitive prosthesis fabrication. According to the current level of evidences, IOS should only be used for short-span prosthesis that follows a confirmative occlusal relationship with the opposing arch.

This is facilitated by scanning the maxillary and mandibular arches when they are at maximal intercuspation. For longer span prosthesis, in addition to accurately recording the tooth surface, the occlusal relationship has to be registered, which is very difficult to record by IOS after preparing several teeth. This recommendation is supported by clinical studies that indicate 3- or 4-unit prostheses fabricated via IOS impressions exhibit similar accuracy to prostheses fabricated by conventional techniques.[1,2,12-15]

There is some evidence that smooth surfaces are easier to capture by light scanners in comparison to irregular and corrugated surfaces.[38,46,47] Thus, if IOS is planned to be implemented, it is reasonable for the clinician to modify the preparation design by ensuring smooth and regular surfaces with rounded internal line angles.[17] On the other hand, areas of sudden change of curvature may suffer from greater deviations.[8] Therefore, sharp preparation edges, grooves and boxes are better avoided. Further, it is easier to replicate the rounded internal line angles by the CAM process on the prosthesis fitting surface.[9] As the preparation is used digitally to design the prosthesis, it has to be easily read by the software. One of the frequently encountered limitations of CAD/CAM systems is the precision of the marginal area.[36] Several studies have indicated that the prosthesis margins are vulnerable to inaccuracy.[23,24] This may be attributed to difficulties in allocating the prosthesis margin virtually. Nevertheless, more research is desirable to provide recommendations to the clinicians regarding preparation margin design, saliva control, cost efficiency and long term outcome.

CONCLUSIONS

Within the limitations of this systematic review, it appears that, for diagnostic purposes and short-span scanning, the accuracy of IOS systems is comparable to the accuracy of conventional impressions. Since the different IOS systems appear to have the potential to provide an outcome of similar accuracy range, no preference for a particular system can be made. There are some indications that smooth and regular surfaces are easier to capture by IOS than irregular and corrugated surfaces.

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