Journal of Dentistry 137 (2023) 104636

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

Review article

Evaluation of the accuracy of intraoral scanners for complete-arch scanning: A systematic review and network meta-analysis

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ARTICLE INFO

Keywords:
Dentated
Edentulous
Implant
Precision
Trueness
Ranking

ABSTRACT

Objectives: This network meta-analysis (NMA) aimed to compare the complete-arch scanning accuracy of different intraoral scanners (IOSs) to that of reference standard tessellation language (STL) files.
Data: Studies comparing the trueness and precision of IOS STL files with those of reference STL scans for different arch types (dentate, edentulous, completely edentulous with implants, and partially edentulous with implants) were included in this study.
Sources: An electronic search of five databases restricted to the English Language was conducted in October 2021.
Study selection: A total of 3,815 studies were identified, of which 114 were eligible for inclusion. After study selection and data extraction, pair-wise comparison and NMA were performed to define the accuracy of scanning for four arch subgroups using four outcomes (trueness and precision expressed as mean absolute deviation and root mean square values). Cochrane guidelines and the QUADAS-2 tool were used to assess the risk of bias. GRADE was used for certainty assessment.
Results: Fifty-three articles were included in this NMA. Altogether, 26 IOSs were compared directly and indirectly in 10 network systems. The accuracy of IOSs scans were not significantly different from the reference scans for dentate arches (three IOSs), edentulous arches (three IOSs), and completely edentulous arches with implants (one IOS). The accuracy of the IOSs was significantly different from the reference scans for partially edentulous arches with implants. Significant accuracy differences were found between the IOSs, regardless of clinical scenarios.
Conclusions: The accuracy of complete-arch scanning by IOSs differs based on clinical scenarios.
Clinical significance: Different IOSs should be used according to the complete arch type.

1. Introduction

Owing to the impact of COVID-19, digital dental technologies have undergone rapid advancements. The global market share of intraoral scanners (IOSs), which was valued at $382.52 million in 2020, is projected to reach $875.60 million by 2030, growing at a compound annual growth rate of 18.6% from 2021 to 2030 [1]. The growing popularity of digital dentistry can be attributed to its role in efficient diagnosis and treatment planning as well as in the fabrication of orthodontic appliances and prostheses [2].

When fabricating a complete dental arch restoration or an orthodontic appliance with a fully digital dental workflow, a standard tessellation language file (STL) is generated using an IOS and is used by the dentist or dental technician to design and manufacture the restoration; therefore, the virtual three-dimensional (3D) impression should be as accurate as possible to obtain a high-quality restoration for the chosen indication. With the introduction of newer generations of IOSs, the accuracy may differ between devices and some may be more suitable for

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https://doi.org/10.1016/j.jdent.2023.104636
Received 21 October 2022; Received in revised form 11 July 2023; Accepted 25 July 2023
Available online 27 July 2023

complete-arch optical impressions than others [3].

Because STL files are composed of virtual 3D coordinates, the accuracy of the IOSs can be investigated using several methods. The measurement of accuracy has two components according to the International Organization for Standardization (ISO) 5725–1: precision and trueness [4]; trueness is the closeness of agreement between the average value obtained from a large series of test results and an accepted reference value, and precision is the closeness of agreement between independent test results obtained under stipulated conditions [5]. The mean absolute deviation (MAD) is commonly used to express accuracy. The root mean square (RMS) is a new modality to assess the absolute distance for all virtual points in the scanned region, thereby determining the trueness and precision values of IOS STL files [6,7]. Although both metrics are widely used, the clinical significance of their differences has not been described in the literature. Reviewing the accuracy of different IOSs presented as MAD and RMS values can help us understand the differences between both and provide guidance regarding the suitable metric for further research. When investigating the accuracy (trueness and precision) of IOSs, it is not sufficient to just highlight the differences between devices; it is also important to define their clinical acceptability for different indications. There is no consensus regarding the clinically acceptable accuracy range of IOS; however, the threshold misfit that does not induce clinical complications ranges between 50 and 200 μm in fixed restorations [8–10]. The misfit of restorations can be a good basis to determine the clinically acceptable accuracy range of IOSs. The marginal film thickness of spark-eroded titanium copings is said to be less than 120 μm (90 ± 44 μm) [11]. In the case of Procera AllCeram crowns, the median maximal marginal gap width ranges from 80 to 180 μm in anterior teeth and from 115 to 245 μm in posterior teeth [12]. In addition, most studies have considered 120 μm as the clinically acceptable misfit based on the original McLean and Fraunhofer study [13].

Several factors influence IOS accuracy [14] for instance, hardware factors (such as different data capture principles) [15], software factors [16,17], scan object factors (such as model materials [18,19], restoration materials [20] span length [21], additional surface modifications [22], and different clinical scenarios [23–26]). Consequently, four subgroups can form where the biggest accuracy differences can be seen: dentate arch, edentulous arch, completely edentulous arches with implants and partially edentulous arches with implants. Further influencing factors are operator factors (such as operator experience [27], and scanning pattern [28,29]), environmental factors (such as ambient light [30], humidity, temperature [31,32], and the presence of saliva or wet conditions [33]), measurement methods (such as coordinate measuring machines, calipers, distance measurements, local fit comparisons, and 3D comparisons [5,34,35]) and reference factors. Our study used STL files generated by laboratory or industrial scanners as a reference. Laboratory desktop scanners have a broad view of areas and can be used as a reference instead of industrial scanners that have proven high accuracy [25,36-38].

Since 2008, the number of articles on IOSs has grown exponentially, reaching approximately 300 articles per year in 2021 [39]. Studies have used a wide range of methods with diverse results, making qualitative and quantitative comparisons of the studies difficult. A systematic review and meta-analysis on digital versus conventional implant impressions confirmed high heterogeneity between studies, and in several systematic reviews, simultaneous meta-analysis could not be performed owing to the high heterogeneity [14,40,41]. As a result, it is difficult to draw conclusions regarding the accuracy of different IOSs. To date, no systematic review or meta-analysis has compared IOSs directly or indirectly in a network meta-analysis (NMA). Clinicians should consider all relevant data when comparing the accuracy of different IOSs, and multiple comparisons can be performed across studies using a network. In fact, an NMA allowed us to estimate the rank probability of IOSs.

The aim of this NMA was to investigate the accuracy, precision, and trueness of complete-arch intraoral scanning with different IOSs and to provide dentists with guidance on choosing the right device for complete-arch scanning through an NMA. The null hypothesis is that there was no statistical difference between IOS STL scans and reference STL scans and that there was no statistically significant difference in the accuracy (precision and trueness) of IOS devices. Additionally, we hypothesized that the accuracy of the 95% confidence interval (CI) of the IOSs was within the clinically acceptable threshold of 120 μm.

2. Materials and methods

2.1. Protocol and registration

The protocol for this review was registered in the PROSPERO database (registration number CRD42021281989) and is freely accessible at https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=281989. The deviation from the protocol included changes from meta-analysis to NMA due to the high number of multi-arm studies. This NMA was conducted according to the PRISMA NMA checklist (*Supplementary material 1*) [42].

2.2. Eligibility criteria

2.2.1. Inclusion criteria

The patient characteristics, index test, reference standard, and outcome (PICO) format was applied to the clinical questions. In the present study, we used multiple- or two-arm studies on primary diagnostic test accuracy studies published in English that reported on complete-arch scanning (P) with IOSs as index tests (I) and use of reference standard STL files for comparison I of accuracy (O). Maxillary and mandibular edentulous or dentate arches and arches with implants were included. Dentate arches included those with natural dentition with or without partial edentulism and with or without tooth preparation. Reference STL files could be generated by industrial or laboratory scanners. Studies determining accuracy (precision and trueness) by superimposition of data were included. Both in vitro and clinical studies were included in this review.

2.2.2. Exclusion criteria

Articles investigating a single tooth, quadrant, or sextant scanning were excluded. Articles in which data on the IOS type were not provided were excluded. Accuracy studies using coordinate measuring machine, computed tomography or caliper were excluded.

2.3. Information sources

Our systematic search included papers published up to October 23, 2021. The search was performed using five electronic databases: Medline, Scopus, Web of Science, EMBASE, and Cochrane Central Register of Controlled Trials (CENTRAL). The databases were searched for English language studies. No filters or restrictions were applied. The reference lists were also checked for potentially eligible articles.

2.4. Search strategy

During the systematic search, the following search key words were used: (“digital impression” OR “intraoral scanner” OR “intraoral scanners” OR “intraoral scan” OR “intraoral scans” OR “intraoral scanning system” OR “intraoral scanning systems”) AND (“arch” OR “complete arch” OR “complete-arch” OR “full-arch” OR “full arch” OR “whole arch” OR “maxilla” OR “maxillary” OR “mandible” OR “mandibular”).

2.5. Selection process

Accuracy studies of diagnostic tests were reviewed to compare the accuracy of IOSs to that of the reference STL files of the full arch. Selection was independently performed according to the set inclusion and exclusion criteria by paired reviewers (VV and AN). After removing duplicates, articles were selected by titles and abstracts and later by full text. Disagreements between the reviewers were resolved by discussion and consultation with a third author (JB). As a measure of inter-rater reliability for the selection of abstracts and full texts, Cohen's kappa coefficients (κ) were calculated.

2.6. Data collection process

Two authors (VV and ES) independently extracted the data using a standardized pre-constructed data extraction form. Disagreements between the data collectors were resolved by a third author (JB). If data were available as median and interquartile range (IQR) values with a normal distribution, they were used for the statistical analysis. Non-normally distributed data were collected only for the systematic review. If different complete arch types or environmental conditions (light source, presence of saliva, and different scanning strategies, among others) were compared within an article, all results were collected for quantitative analysis; however, for the qualitative synthesis, information on the following was used to reduce inconsistencies across the reports: normal dentition without crowding, prepared teeth, implant impressions made only with scan bodies, scanning strategy of the manufacturer, dry surfaces, room light conditions, and experienced operator. Automation tools were not used in this process.

2.7. Data items

The following information was extracted: name of the first author, year of publication, aim, type of complete arch (dentate, edentulous, and so forth), number of STL files, reference scanner, scanning strategy, scanner software version, inspection software, superimposition type, operator, light condition, measured distances, trueness and precision MAD, standard deviation (SD), RMS mean deviation and SD, and other outcome parameters indicating accuracy.

2.8. Risk of bias within the studies

The risk of bias was assessed using the Cochrane Risk of Bias Tool for Primary Diagnostic Accuracy Studies (QUADAS-2) for each outcome. The risk of bias was independently judged as "low," "unclear," or "high" [43] by two authors, and any disagreement was resolved by consulting a third author.

2.9. Summary measures and synthesis of results

A network plot was created for each subgroup to determine if the resulting network was fully connected. Based on these network plots, all subgroups were eligible for the NMA. The basic characteristics of each analysis were reported using network and study characteristic tables containing the most important statistics from each NMA. A detailed description of the statistical analysis is provided in *Supplementary material 2*. All statistical analyses were performed using R software (ver. 4.1.3.) supplemented with the BUGSnet package [44,45].

2.10. Exploration for inconsistency

Both consistency and inconsistency models were created from the same dataset and then compared to determine data heterogeneity.

2.11. Certainty of evidence

For each outcome assessed in the NMA, the quality of evidence was assessed in duplicate according to the Grades of Recommendation, Assessment, Development, and Evaluation Working Group recommendations using a modified GRADE approach [46].

2.12. Additional analysis

Subgroup analysis was performed according to the different complete arch types, namely dentate, edentulous, completely edentulous with implants, and partially edentulous with implants. Additionally, the RMS and MAD values were investigated in different subgroups for precision and trueness.

3. Results

3.1. Study selection

In total, 3815 studies were identified using the search key words. Of these studies, 2121 were screened, and 114 diagnostic test accuracy studies were included in this review, 53 of which contributed to the NMA (Fig. 1). The list of excluded papers and reasons for exclusion are presented in *Supplementary material 3*. Cohen's kappa coefficient for title and abstract selection was 0.88 and that for full-text selection was κ =0.9, indicating a near-perfect agreement.

3.2. Study characteristics

All included studies were published in English between 2012 and 2022. Twenty-six IOSs were used in the study. The abbreviations used for the scanners are listed in *Supplementary material 4*. The characteristics of the articles are detailed in *Supplementary material 5*. For complete dental arches, five of 21 IOSs for trueness and five of 18 IOSs for precision were mentioned only in one article. For edentulous arches, the ratio was two of nine IOSs for trueness and three of nine in the precision group. For edentulous arches with implants, nine of 17 IOSs for trueness group and six of 12 IOSs for precision were investigated once. For partially edentulous arches with implants the ratio was seven of 12 IOSs for trueness and five of 10 for precision were studied.

3.3. Studies included in NMA

The basic characteristics of the 53 selected studies are summarized in *Supplementary material 5*. Studies comparing the scans of one or more IOSs to the reference digital files generated by industrial or laboratory scanners on the same complete arch were published between 2013 and 2021. Among the 26 IOSs, the most commonly used were 3Shape Trios 3 (TR3) (54.72%), CEREC Omnicam (Omn) (35.84%), and CEREC Primescan (Pri) (20.75%) considering the intervention arms. The most common comparators were industrial scanners (60.38%). Four subgroups were created according to the type of complete arch: dentate arch, edentulous arch, fully edentulous arch with implants, and partially edentulous arch with implants. The accuracy results were categorized as MAD trueness and precision groups for all subgroups. In the complete dentate arch subgroup, sufficient data were obtained for RMS trueness and precision analysis.

The network plot, rankograms and league heat plots show the IOS-ranking hierarchy in the MAD values of precision and trueness in dentate arches in Figs. 2 and 3. All subgroup network plots, rankograms, league-heat plots, and forest plots are included in *Supplementary material 6* (*Fig. 1-10, Table 1-10*).

3.4. Risk of bias within studies

Of the 53 studies, 33 were assessed as having unclear risk and 11 as being high-risk because of a lack of information on the IOS software version, scanning strategy, operator, sample size, and light conditions. The results of the risk-of-bias assessment are presented in *Supplementary material 7*.

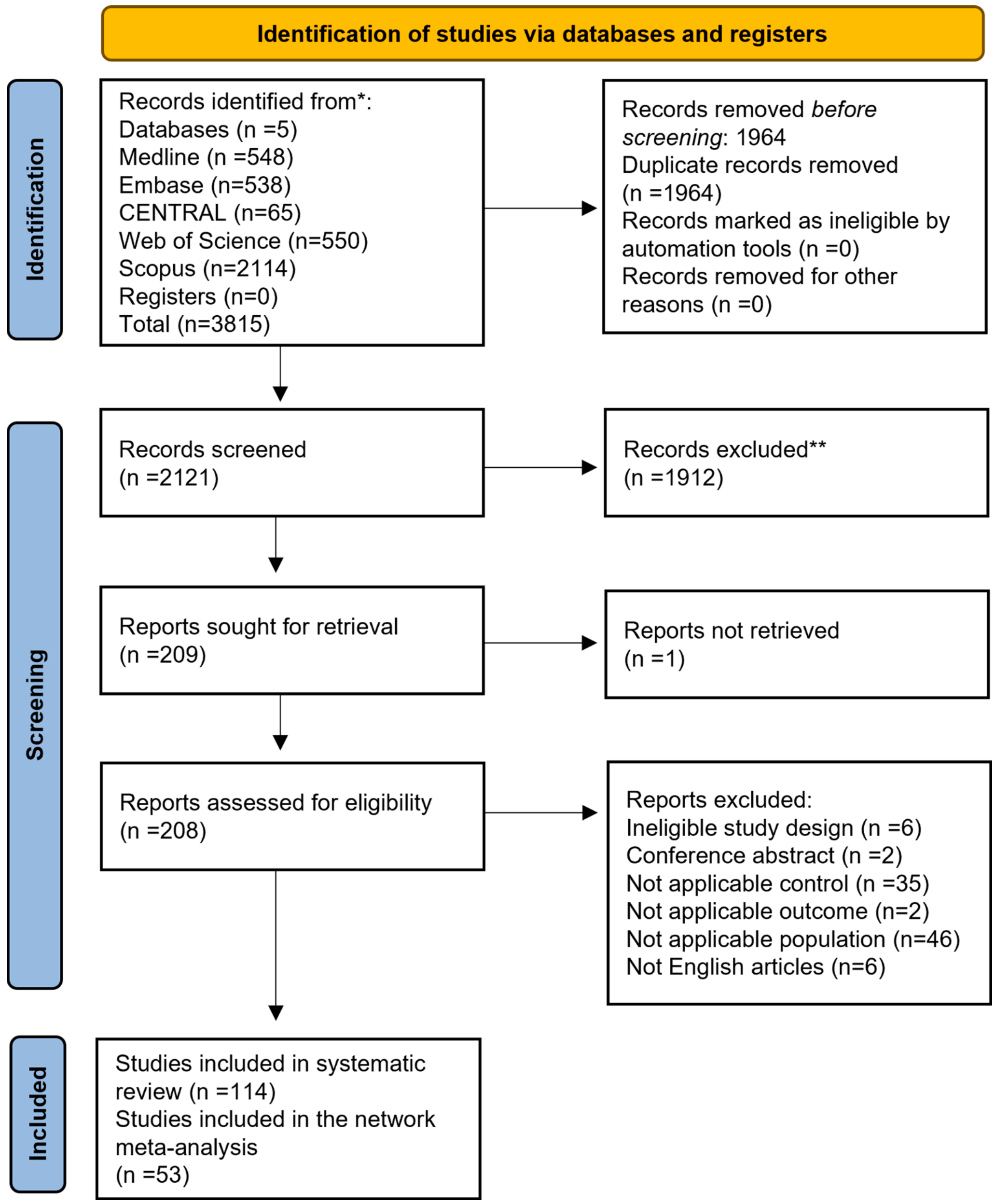

Fig. 1. PRISMA flow program for study selection.

3.5. Results of individual studies

Of the 53 studies, one was a clinical study on healthy patients [47], two used human cadavers [48,49], and 50 were in vitro studies [19,23,26,27,50-83]. In 45 studies, trueness was assessed based on the MAD, the median and interquartile range (IQR) were used in one study [53], the mean RMS SD were considered in seven, the median RMS and IQR were considered in one [84], and RMS error was considered in one study [85]. Precision was described as MAD values in 29 studies, as median and IQR values in one [78], median RMS and IQR in two [7,86], and mean RMS and SD in five. The median and IQR results were converted to mean and SD when the data were normally distributed. The trueness and precision of the results of the individual studies are listed in *Supplementary material 8*.

3.6. Synthesis of results and rank probabilities

Trueness for dentate arches (MAD). The trueness analysis for the complete dentate arch included 24 studies [19,30,47,48,53,62-72,74-79,87,88], 31 arches, and 21 IOSs. Scans of six of the 21 IOSs showed no significant difference compared to the reference scans: 3Shape Trios 2 (TR2), iTero Element 1 (iT1), FastScan (Fast), 3Shape Trios 4 (TR4), 3 M Lava (Lava), Runyes Quickscan (Run). The 95% CI of the six IOSs was within the clinically acceptable threshold of 120 μm: Pri, TR2, iT1, TR3, Medit i500 (i500) and iTero Cadent (iTC) (Fig 2). Although the previous generations of CEREC IOSs, CEREC Bluecam (Blu) and Omn had poor trueness, Pri had the best results for complete dentate arches. The ITero IOSs also performed well and showed no significant differences between generations. Considering the 3Shape IOSs, the newer generations (TR4, TR3) were not better in trueness than the older device (TR2). The i500 IOS also had acceptable trueness.

Precision for dentate arches (MAD). The precision analysis for complete dentate arches included 14 studies [7,19,26,30,47,48,68,69,71,74,75,77-79]17 arches, and 18 IOSs (Fig. 3a). Scans with 13 of 18 IOSs showed no significant difference compared to the reference scans: Omn, Carestream 3600 (CS36), Planmeca Emerald (Eme), Zfx IntraScan (Zfx),

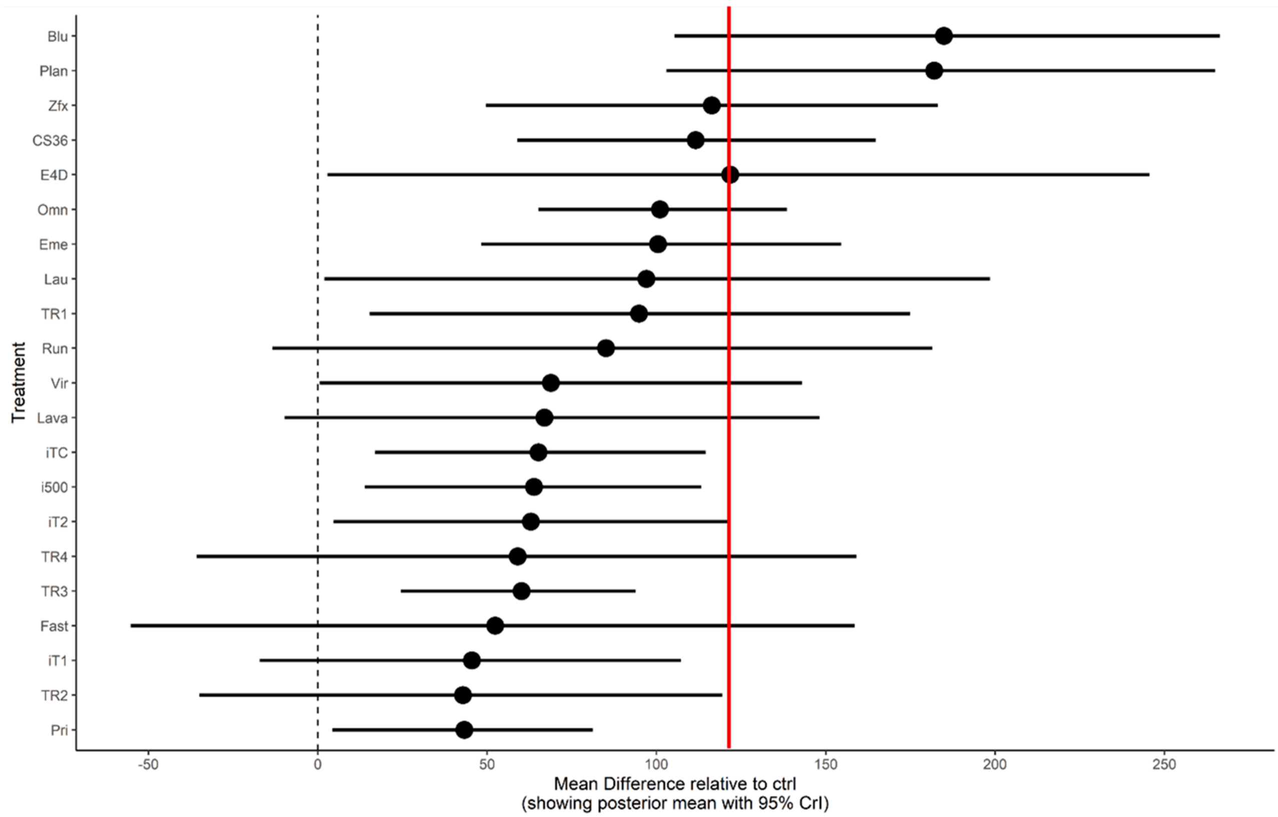

Fig. 2. Forest plot showing the trueness of different IOSs and their mean difference relative to the control with 95%CI in the dentate arch group. Null-effect line (X-axis=0): the value of the control group (reference STL file), in this case 0, as the trueness of the gold-standard STL-files should be 0. X-axis: the performance of each IOS (mean and CI) compared to the reference scanner group. The further the interval is from the null-effect line, the worse the performance of the index-test is. Y-axis: the different index tests ordered by performance. The 120 μm threshold is marked with red line.

and iT1 are the exceptions) (Fig. 3b). There was no significant difference between the IOSs. The 95% CIs of the FasI, i500, TR3, Pri, iTC, and iTero Element 2 (iT2) IOSs were within the clinically acceptable threshold of 120 μm. Fast and i500 had very good precision in the dentate models. The 3Shape IOSs showed acceptable precision. Pri from CEREC IOSs had better precision than that of previous generation IOSs (Blu and Omn). The newer generation of iTero IOS (iT2) showed significantly better precision than the older generation (iT1).

Trueness for dentate arches (RMS). The RMS trueness analysis for dentate and prepared models included 11 studies [6,7,33,84,86,89-94], 13 arches, and 10 IOSs. The ranking probabilities were as follows: scans of two of the 10 IOSs showed no significant difference compared to the reference scans (Lava, Pri). The ranking of IOSs was similar to that indicated by MAD values for dentate arch trueness. The newer generations of 3 M, CEREC, 3Shape, and Carestream IOSs have better trueness than that of their older generations.

Precision for dentate arches (RMS). The RMS precision analysis for dentate and prepared models included seven studies [7,33,84,86,90,91,93], nine arches, and eight IOSs. Scans with seven of the eight IOSs showed no significant difference compared with the reference scans: Planmeca Planscan (Plan) is the exception). There was no significant difference between the IOSs, except for the Planmeca Plan IOS, the precision of which differed significantly from that of all other IOSs.

Trueness for edentulous arches (MAD). The trueness analysis for complete edentulous arches included five studies [49-53,95], eight arches, and nine IOSs. Scans of four of the nine IOSs showed no significant difference compared to the reference scans (Lava, Pri, iT2, TR4). The trueness of only Lava and Pri IOSs was within the clinically acceptable threshold of 120 μm. Although the data in this group indicate that intraoral scanning of edentulous sites is challenging, Pri and Lava IOSs had clinically acceptable trueness. The precision findings of iTero and 3Shape IOSs are also promising, with statistically insignificant differences between them.

Precision for edentulous arches (MAD). The precision analysis for complete edentulous arches included four studies [49–52], six arches, and nine IOSs. Scans of five of the nine IOSs showed no significant difference compared to the reference scans (Pri, iT2, TR3, Lava, and i500). The 95% CIs of Pri, iT2, TR3, Lava, and i500 IOSs were within the clinically acceptable threshold of 120 μm. The newer generations of CEREC (Pri) and iTero (iT2) IOSs showed the best results for precision in edentulous arches. The 3Shape, 3 M, and Medit IOSs also showed clinically acceptable precision.

Trueness for edentulous arches with implants (MAD). The trueness analysis for complete edentulous arches with implants included nine studies [9,54,56-61,96], nine arches, and 17 IOSs. Scans of nine of the 17 IOSs showed no significant difference compared to the reference scans: TR2, 3Shape Trios 1 (TR1), Carestream 3700 (CS37), Blu, CS36, Planmeca Emerald S (Eme S), Carestream 3500 (CS35), Eme, and Nevo E4D (E4D). The trueness of only the TR1 IOS was within the clinically acceptable threshold of 120 μm (TR2, CS36, Omn, and TR3 were close to the threshold). The trueness with newer generation 3shape IOSs was not better than that with the older generations; however, the difference was not statistically significant. In contrast, the newer generations of the Carestream and Planmeca IOSs performed better than the older ones.

Precision for fully edentulous arches with implants (MAD). The precision analysis for edentulous arches with implants included seven studies [23,54,56,60,61,96], seven arches, and 12 IOSs. Scans of four of the 12 IOSs showed no significant difference compared to the reference scans: Straumann Virtuo Vivo (Vir), TR3, TR1, and 3 M True Definition (TRU). The precision of nine IOSs was within the clinically acceptable threshold of 120 μm: Zfx, Straumann DWIO (DWIO), and Plan were exceptions. The newer generations of 3Shape (TR3), Straumann (Vir), Carestream

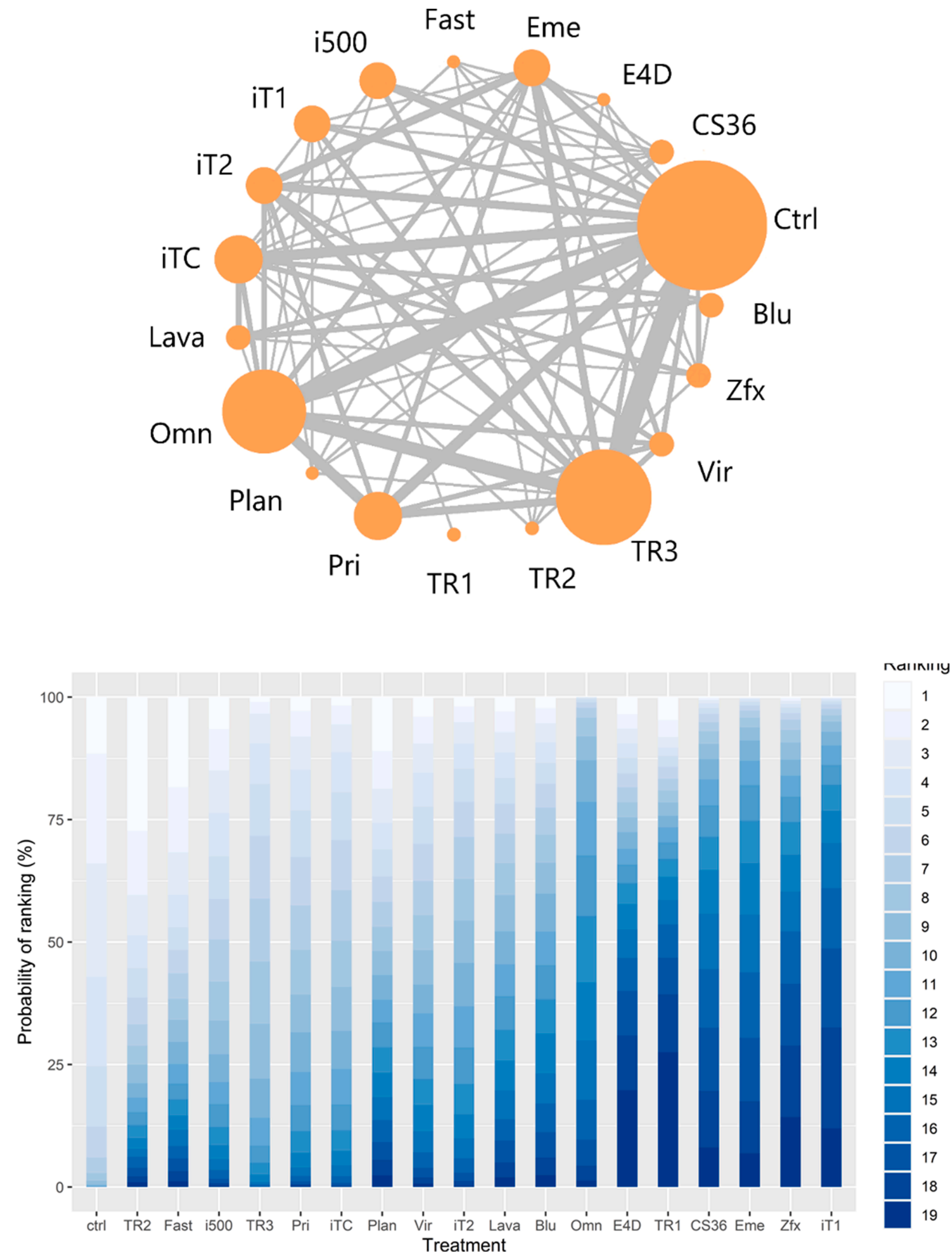

Fig. 3. Precision of dentate arch a) Network plot containing 14 studies and 18 IOS. b) Rankogram showing the ranking probability of IOS.

(CS36), and Lava (TRU) IOSs had better precision than the older devices (TR1, DWIO, CS35, Lava).

Trueness for partially edentulous arches with implants (MAD). The trueness analysis for partially edentulous arches included seven studies [23,27,55,80-83], seven arches, and 12 IOSs. Scans of all IOSs showed a significant difference compared to the reference scans. The trueness of the TRU, CS35, TR1, and TR3 IOSs was within the clinically acceptable threshold of 120 µm, and that of Vir was very close to the threshold. The newer generation 3 M (TRU) and older generation Carestream (CS35) and 3Shape (TR1, TR3) IOSs had clinically acceptable trueness.

Precision for partially edentulous arches with implants (MAD). The precision analysis for partially edentulous arches included six studies [23,27,55,80-82], six arches, and 10 IOSs. Scans of six of the 10 IOSs showed no significant difference compared to the reference scans (TRU, CS35, TR3, Vir, Pri and Zfx). The precision of none of the IOSs was within the clinically acceptable threshold of 120 µm.

The mean MAD values for all IOSs and subgroups ranged between 35.37 µm and 581.43 µm for trueness and between 4.72 µm and 355.51

μm for precision. IOSs with CI under the clinically acceptable threshold off 120 μm had mean trueness between 42 μm and 76.28 μm and mean precision ranging from 5.48 μm to 60.75 μm. The mean RMS values ranged between 27.55 μm and 389.02 μm for trueness and from 39.5 μm to 561.45 μm for precision. All IOSs accuracy results are presented in Table 1.

Considering both trueness and precision, the accuracy of the IOSs was not significantly different from the reference scans in the dentate arches (three IOSs), edentulous arches (three IOSs), and completely edentulous arches with implants (one IOSs). The accuracy of all IOSs was significantly different for partially edentulous arches. Significant differences were found between the IOSs.

Of the 18 IOSs investigated for accuracy in dentate arches (MAD), only four IOSs (Pri, TR3, i500, iTC) showed clinically acceptable accuracy, with the CI of the trueness and precision below 120 μm. For edentulous arches, only one of nine IOSs (Pri) showed clinically acceptable accuracy. For completely edentulous arches with implants, one IOS (TR2) of the 12 showed clinically acceptable accuracy. None of the IOSs were clinically acceptable for partially edentulous arches (*Supplementary material 9*).

3.7. *Exploration for inconsistency*

With the random-effects model

Consistency-inconsistency model check

The consistency-inconsistency plot indicates some bias or concern regarding the relationship between different IOSs. Inconsistency can be seen when the data points fall further below the 45° line in the plot. In

Table 1
Accuracy (trueness and precision) of IOSs in different clinical scenarios.

IOS	dentate arches (MAD)		edentulous arches (MAD)		partially edentulous arches with implants (MAD)		fully edentulous arches with implants (MAD)	
	Trueness	Precision	Trueness	Precision	Trueness	Precision	Trueness	Precision
iTC	**64.85** (14.3, 116.62)	34.76 (−28.69, 101.39)			**102.01** (76.91, 127.04)	**193.71** (99.39, 288.03)		
iT1	45.66 (−16.35, 109.12)	**103.81** (21.3, 185.58)	**147.44** (63,09; 230,41)	**172.46** (93.66, 250.75)				
iT2	**62.5** (3.0, 122.51)	44.13 (−25.88, 116.04)	73.11 (−12.81, 160.87)	6.99 (−58.35, 74.8)				
TR1	**93.44** (14.61, 175.16)	99.64 (−63.65, 254.6)			**65.15** (41.07, 89.72)	**142.95** (59.69, 226.48)	47.88 (−22.53, 116.3)	27.76 (−14.24, 71.99)
TR2	42 (−38.12, 122.81)	4,72 (−114.52, 129.88)					35.37 (−56.08, 132.15)	
TR3	**60.41** (26.49, 97.71)	31.5 (−16.24, 77.24)	**87.57** (31.9, 145.02)	9.86 (−33.94, 53.04)	**76.28** (55.72, 97.31)	68.36 (−17.71, 152.95)	**76.99** (33.12, 120.3)	13.33 (−6.43, 33.5)
TR4	59.47 (−36.47, 155.52)		72.98 (−14.10, 161.29)	**78.81** (12.55, 147.46)				
Plan	**182,63** (98.95–265.64)	37.96 (−77.37, 147.54)			**235.89** (168.97, 303.79)	**222.24** (83.34, 367.88)	**303.88** (233.42, 377.13)	**181.49** (135.73, 224.11)
Eme	**99.86** (47.46, 153.7)	**89.30** (20.72, 159.32)					78.62 (−13.56, 170.41)	**42.74** (1.91, 83.32)
Eme S					**100.39** (63.09, 138.82)		53.25 (−55.23, 161.89)	
CS35					**50.17** (13.27, 89.31)	43.75 (−93.41, 185.61)	65.54 (−8.34, 137.12)	**42.3** (10.41, 73.61)
CS36	**111.43** (59.43, 165.4)	**89.17** (7.65, 171.25)			**92.19** (55.61, 130.8)		57.35 (−10.96, 126.02)	**29.72** (0.91, 60.27)
CS37							42.42 (−67.6, 153.01)	
Zfx	**115.85** (49.05, 180.77)	**97.16** (4.13, 192.97)	**264.4** (146.98, 383.59)	**324.98** (210.14, 437.36)	**118.79** (72.4, 163.01)	128.97 (−9.59, 272.97)	**116.68** (18.8, 211.43)	**90.37** (44.04, 133.56)
Blu	**185.15** (105.69, 268.87)	56.65 (−33.17, 144.42)	**581.43** (279.53, 859.16)	**355.51** (185.52, 521.6)			49.77 (−44.45, 142.2)	
Omn	**101,27** (64,36; 138,91)	**72.75** (23.78, 126.16)			**107.94** (88.01, 128.4)	**157.4** (83.99, 229.42)	**74.96** (25.94, 125.15)	**55.5** (31.84, 80.91)
Pri	**43.03** (3.33, 81.39)	33.17 (−27.94, 97.9)	53.29 (−4.49, 110.38)	5.48 (−63.85, 77.19)	**104.8** (58.41, 150.69)	70.35 (−61.05, 200.88)		
Lava	66.31 (−11.45, 146.28)	50.51 (−37.7, 142.05)	48.21 (−25.26, 120.12)	11.04 (−42.76, 63.93)			**132.28** (36.98, 226.77)	**60.75** (18.06, 104.72)
TRU					**42.93** (20.83, 65.37)	44.35 (−38.15, 127.54)	**78.03** (10.9, 149.77)	**33.71** (0.88, 70.62)
DWIO							**104** (9.59, 197.67)	**92.19** (52.24, 134.12)
Vir	68.28 (−3.39, 140.09)	39.92 (−40.05, 121.8)			**84.34** (43.29, 125.98)	67.22 (−60.77, 193.04)	**84.63** (9.26, 158.76)	10.59 (−19.82, 40.92)
i500	**63.66** (14.25, 113.08)	27.58 (−41.88, 97.91)	**104.19** (39.92, 172.2)	23.98 (−27.88, 77.28)				
Fast	52.14 (−54.32, 160.57)	16.82 (−102.44, 136.69)						
Lau	96.38 (−2.04, 196.92)							
Run	84 (−15.43, 182.34)							
E4D	**121.97** (3.44, 243.27)	87.79 (−54.46, 227.96)					87.58 (−4.7, 181.71)	

Mean (CI) in μm.
** ** showing CI is statistically significant from the reference.

the direct and indirect evidence, imbalances in the distribution of effect modifiers may have contributed to inconsistency. These modifiers cannot be completely eliminated in large multi-treatment NMAs, leading to some inconsistency and indicating the need for careful interpretation of the results [97]. However, on examining each outcome, it was concluded that no data point deviated significantly from the consistency-inconsistency line. All inconsistency plots are available in *Supplementary material 10*.

3.8. Certainty of evidence

Regarding the accuracy outcome of all included studies, the confidence rating of IOSs generated through GRADEPRO had low certainty values; however, the outcome was critical every time *(Supplementary material 11)*. The reasons for downgrading of the quality of evidence were serious inconsistencies and indirectness. Major inconsistencies were observed owing to the different measurement methods used across studies. Most articles have investigated dental models rather than patients. A wide range of CIs was also a downgrading factor. Consequently, no conclusions could be drawn about the trueness and precision of IOSs directly for intraoral use.

4. Discussion

The aim of this NMA and systematic review was to investigate the accuracy, precision, and trueness of various IOSs for complete-arch scanning. According to our results, significant differences were found between the reference and IOS STL files as well as between IOSs in complete-arch scanning. The IOS STL files were outside the range of the clinically acceptable threshold of 120 μm. Therefore, our hypothesis was rejected. Furthermore, our results highlight that IOS accuracy may be influenced by scanned arch parameters, such as dentulism, edentulism, complete edentulism with implants, and partial edentulism with implants.

As TR3 was the most investigated device, there is greater evidence on it. This is in contrast with Launca Dl-206 (Lau), which has been investigated in only one study; a smaller sample size can result in a wider range of CIs.

The absolute mean results represented as forest plots enable easy visualization of the statistically significant effect of sample sizes. The null-effect line (X-axis) represents the value of the control group, which in this case was at 0, as the trueness and precision of the gold-standard STL files should be close to 0. If the CI touches the null effect line, the difference from the reference is considered statistically significant. When the sample size increased, the CI became narrower. In some cases, a wide CI can indicate clinical unacceptability. Therefore, the data from a small number of articles should be handled with caution.

The types of complete arches scanned in the included studies, ranging from completely edentulous models to dentate arches of patients, caused great heterogeneity. Creation of subgroups helped reduce the heterogeneity to some extent, but standardization was still complicated as more than 65,000 combinations are possible according to the position of missing teeth [98].

The stitching mechanism can influence scanning accuracy [99], but the deviation along the whole arch deviation should be acceptable to obtain a good quality scan for the prosthetic workflow. Local accuracy is also essential. Zimmermann et al. found that the mean local trueness and precision of the IOS were 18.7 μm and 8.3 μm (CEREC Primescan), respectively; in our study, they were 43.35 μm and 67.51 μm, respectively [100]. Mangano et al. detected similar accuracy through local implant measurements, where CEREC Primescan had the lowest MAD (25.5 ± 5.0 μm) [101]. Further comparisons should highlight both accuracy measurements.

As not only statistically significant but also clinically significant differences were found between IOSs, studies comparing direct and indirect digital workflows with a limited number of IOSs should be analyzed. The results on using an IOS with poor accuracy can indicate that the direct method is not as good as the indirect method. However, using an IOS with clinically acceptable accuracy can also cause bias and suggest that all IOSs are better than the indirect method [102,103].

The cumulative ranking of accuracy shows the summarized ranking probabilities for trueness and precision (*Supplementary material 9*). No other study has assessed the two values together, although both show significant deviations. Ranking probabilities were calculated according to the mean values and did not provide information regarding the 95% CIs. Therefore, the results were also investigated in connection with the clinically acceptable range, where CI was taken into consideration for the threshold. The number of articles on the trueness and precision of IOSs were comparable. However, IOSs with findings of only trueness or precision were not included in the Cumulative Ranking.

Dentate arches have been the most widely investigated among the dental arches. According to the results, Pri, TR3, i500, and iTC IOSs were found to be clinically acceptable for scanning a complete dentate arch. Furthermore, scans with TR2, Lava, Vir, and Fast were not significantly different from the reference scans in terms of trueness or precision based on the MAD outcomes. Similar results were found in the RMS dentate subgroup, in which there were no statistical differences between Lava and Pri. The findings indicate that IOSs can produce accurate digital impressions of complete dentate arches, but not all IOSs are suitable for this purpose. A systematic review and meta-analysis comparing conventional and digital impressions of complete dentate arches showed that the trueness of IOS impressions was similar to that of conventional impressions, and their precision was high [104]. Another meta-analysis showed that digital impressions were comparable to conventional impressions in relation to the marginal fit of complete-coverage, fixed-tooth-supported prostheses [105].

RMS is a metric used for evaluating accuracy with increasing popularity as it provides more information on 3D deviations. According to our results, the RMS values were higher than the MAD values. In the case of CEREC Omnicam, the average MAD of trueness was 101.27 μm, and the trueness value almost doubled when assessed based on the mean RMS (197.9 μm). Abduo et al. found similar results for RMS trueness in their study, where they compared the accuracy of conventional and digital impressions in RMS values. The RMS trueness indicated the greatest accuracy for polyvinyl siloxane impressions (134.7 ± 6.2 μm) followed by STL impressions made with a laboratory scanner (139.1 ± 3.9 μm), alginate impressions (141.7 ± 3.3 μm), and STL impressions with CEREC Omnicam (167.0 ± 4.9 μm) [106].

There were not enough studies on the RMS group using clinical scenarios other than dentated arches for statistical analysis. Of the six articles which were not used in the statistical analyses, one article used edentulous arch [107], three articles used edentulous arches with implants [108,109,110], and two other articles dentated models [99,111]. These studies varied more in their research methodologies. Another problem was the different outcomes in RMS, which could not be calculated into one homogenous result. In three articles RMS median were used [109,110,111]. In one article the results were not absolute values [99]. In the future, when we have enough standardized studies for statistical analysis, it would be fascinating to analyze these data as well.

The data suggest that it is challenging for IOSs to capture edentulous areas as scans of only one IOS (Pri) showed both clinically and statistically insignificant differences from the reference scans. Although Lava and iT2 scans were not significantly different from the reference scans, their accuracy was not clinically acceptable. Although no systematic review has been published on the accuracy of digital impressions in edentulous arches, it is clear that there is a need to improve digital edentulous scans [22,107].

A similar problem is encountered when scanning implants in totally or partially edentulous arches. There was only one IOS (TR2) that was clinically and statistically not significantly different from the reference scans in the totally edentulous arch; moreover, in the partially edentulous arch, none of the IOS STL files were clinically acceptable, and all IOS STL files showed statistically significant differences from the reference scans. A systematic review and meta-analysis published in 2020 showed that the 3D accuracy of digital impressions made by IOSs and conventional implant impressions was comparable. However, they recommended further research before application of IOSs in routine clinical practice [112]. Another systematic review determined that the accuracy of scanning completely edentulous arches is affected by several factors: type of IOS, scan pattern, environmental conditions, distances between implants, angle of implant, and material [113]. Full-arch digital implant impressions obtained using IOSs were also not sufficiently accurate for clinical application, according to a systematic review on full-arch implant impressions [41].

This is the first systematic review and NMA on the accuracy of IOSs. The number of direct and indirect comparisons was high in the NMA subgroups, providing strong evidence. This network analysis involved comparison of a wide range of IOSs at the same time. Estimating the relative ranking based on trueness, precision, and accuracy, can help rank the IOSs in order of their superiority [43]. This study collected information on not just one anatomical landscape of the intraoral cavity and showed the accuracy of IOSs for various complete arch types. Consequently, guidelines can be established according to the IOS accuracy in different anatomical situations for the use of different IOSs.

Considering the limitations of this study, not every subgroup had sufficient data on a wide range of IOSs. There is not enough data on all the IOSs available in the market; therefore, this should be considered when interpreting the ranking system. There are IOSs that have been mentioned only in one article; therefore, data on them provide less evidence than data on IOSs mentioned in more than one article. Most studies used models rather than patients; therefore, the accuracy may differ when IOSs are used in patients. The presence of moderate and high risks of bias is another limitation. A further weak point is the 120 μm value is not a gold standard or a recommendation; rather, it is related to the "marginal fit" of the prosthesis, making it difficult to apply the threshold to assess the accuracy of IOSs. The fit of the prosthesis would typically, but not always, be less than 120 μm if the accuracy of IOSs is within 120 μm. This is a clear limitation because numerous aspects are involved in prosthesis production that might lead to errors. The results would be interpreted differently depending on how one sets that clinically acceptable value. There is no established consensus or guideline for the acceptable range or value of IOS accuracy at the current knowledge base.

It is crucial to translate scientific results into clinical practice as soon as possible [114]. When scanning a complete arch, dentists should choose an IOS that best fits the indication. *Supplementary material 9* lists the ranking probabilities for different complete arch types according to different clinical scenarios. Pri, TR2, TR3, i500, iTC, iT2, Lava, Vir and Fast IOSs are suitable for scanning complete arches, while Plan, Blu, Zfx, E4D, Lau, and DWIO IOSs are not recommended due to lack of data or insufficient results on accuracy. Plan, Zfx, and Blu IOSs are used for quadrant scans, and complete-arch scanning is not recommended by their manufacturers, which is consistent with our results on IOS accuracy.

Based on our results, the use of a standardized accuracy assessment protocol is suggested for IOS (caliper, conventional impression, and coordinate measuring machine, among others). Future studies should use a standardized reporting protocol for scanning details (light conditions and scanning sequence, among others). Standardized multi-arm clinical trials are required for several IOSs. A guideline was published in 2021 about the basic terms of accuracy in the context of digital dentistry. It included the application of ISO norms and their expansion to special aspects concerning 3D data acquisition and in particular, surface meshes [115]. Similar guidelines are needed for further research; it is also necessary to standardize the reference scanners used. Laboratory scanners are good options to create reference data but should be validated before use in IOS-evaluation studies [38].

Further investigations are needed to assess the accuracy of other IOSs available in the market to develop up-to-date guidelines on selecting the most suitable IOS for complete-arch intraoral scanning. Further in vivo studies are required to provide more evidence in dental practice. Researchers comparing digital impressions and digital technology with conventional impressions and methods should consider the great differences between IOSs, which can significantly affect outcomes.

5. Conclusions

In conclusion, with some exceptions, IOS systems are sufficiently accurate for generating clinically acceptable complete-arch digital impressions. The accuracy of IOSs for complete arches can differ under various clinical scenarios. IOSs do not provide accurate complete-arch digital impressions in cases with implants. Differences were found between the various IOSs. The newer generation IOSs are not always the most accurate devices, but there is a visible tendency for an increase in accuracy over time with advances in IOS technology.

CRediT authorship contribution statement

Viktória Vitai: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Anna Németh:** Investigation, Validation, Writing – review & editing. **Eleonóra Sólyom:** Investigation, Writing – review & editing. **László Márk Czumbel:** Conceptualization, Methodology, Supervision, Project administration, Methodology, Writing – review & editing. **Bence Szabó:** Formal analysis, Data curation, Writing – review & editing. **Réka Fazekas:** Writing – review & editing, Supervision. **Gábor Gerber:** Writing – review & editing, Supervision. **Péter Hegyi:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Péter Hermann:** Writing – review & editing, Supervision. **Judit Borbély:** Conceptualization, Methodology, Validation, Project administration, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jdent.2023.104636.

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