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Non-invasive oral implant position assessment: An ex vivo study using a 3D industrial scan as the reference model to mimic the clinical situation

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Dentsply Sirona Implants

Abstract

Aim: To introduce an objective method to evaluate the accuracy of implant position assessment in partially edentulous patients by comparing different techniques (conventional impression, intraoral scan, CBCT) to a reference 3D model obtained with an industrial scanner, the latter mimicking the clinical situation.

Materials and Methods: Twenty-nine implants were placed in four human cadaver heads using a fully guided flapless protocol. Implant position was assessed using (a) a conventional impression, (b) an intraoral scan, and (c) CBCT and compared to an industrial scan. Three-dimensional models of intraoral scan body and implant were registered to the arch models and the deviation at implant shoulder, apex, and the angle of deviation were compared to each other as well as to the reference model.

Results: The three assessment techniques showed statistically significant deviations ($p < .01$) from the industrial scan, for all measurements, with no difference between the techniques. The maximum deviation at the implant shoulder was 0.16 mm. At the implant apex this increased to 0.38 mm. The intraoral scan deviated significantly more than the CBCT (0.12 mm, $p < .01$) and the conventional impression (0.10 mm, $p = .02$). The maximum implant angle deviation was 1.0°. The intraoral scan deviated more than the conventional impression (0.3°, $p = .02$).

Conclusion: All assessment techniques deviated from the reference industrial scan, but the differences were relatively small. Intraoral scans were slightly less accurate than both conventional impressions and CBCT. Depending on the application, however, this inaccuracy may not be clinically relevant.

KEYWORDS

accuracy, CBCT, conventional impression, implant position, intraoral scan, oral implant

1 | INTRODUCTION

Accurately assessing the position of oral implants is fundamental to obtaining well-fitting prosthetic restorations. Additionally, research questions regarding the accuracy of various surgical protocols, such as static computer-aided implant surgery (s-CAIS), can only be answered properly if the position of the placed implant can be accurately compared to the pre-operative virtual planning.

Intraoral scanners have entered clinical practice and promise to provide many advantages over conventional impressions (Siqueira et al., 2021). When determining the position of an implant using an intraoral scanner, an intraoral scan body (ISB) is used, a component which is inserted into the implant and provides the intraoral scanner with distinct reference points, allowing the software to determine the implant position based on manufacturer information regarding the implant-to-scan body relation (see Figure 1a). The accuracy of intraoral scans seems to be comparable with that of conventional impressions under laboratory conditions, but in vivo studies mostly compare different impression techniques with each other without a "gold standard" reference (Papaspyridakos et al., 2016; Wismeijer et al., 2018). Regardless of the impression technique, inaccuracies at this stage may lead to improper fit of the prosthetic restoration, potentially causing biological and technical complications.

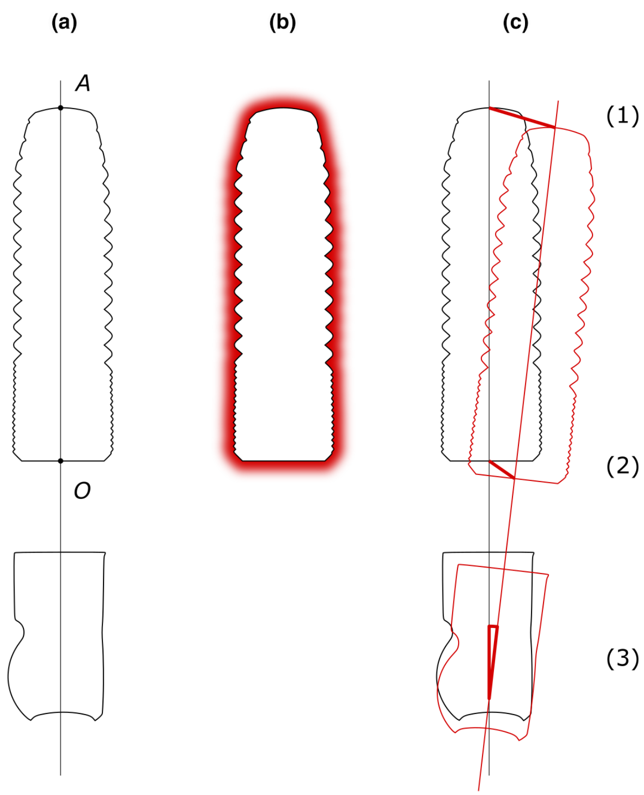

FIGURE 1 Implant-to-scan body relation (a) and sources of error when determining implant position: blooming artifacts when using CBCT scans (b), and deviation in intraoral scan body (ISB) registration (c). Measurements were defined as deviation at implant apex (1), deviation at implant shoulder (2) and deviation angle (3). Adapted from Van Assche et al. (2012).

Implant position assessment also has important research applications, wherever the position of the implant needs to be compared to an "ideal" planned position, as in guided surgery, or when implant migration needs to be evaluated (Becker et al., 2019). Multiple protocols have been proposed for evaluating implant placement accuracy when using surgical guides. Most rely on the use of post-operative CBCT, based on which the comparison between the actual implant position and the planned implant position is made using specialized software. This software is usually supplied by the surgical guide vendor or performed in-house by the vendor itself. While this approach may represent the current gold standard, it has important limitations: it requires a post-operative CBCT to be taken strictly for research purposes, thereby exposing the patient to additional ionizing radiation, exposure which current guidelines recommend "should be examined and approved by an ethics committee, set up in accordance with national procedures and/or by the competent authorities" (Harris et al., 2012). Additionally, the resulting image is affected by blooming artifacts due to the presence of metal, making it impossible to determine the exact position of the implant, and whether a thin (<0.3 mm) plate of bone is present around it (Vanderstuyft et al., 2019, see Figure 1b). Furthermore, the methodology used in these studies is often non-reproducible, as it requires agreements with implant manufacturers and access to specialized software.

Recently, the use of scan bodies and an intraoral scanner has been suggested (von See et al., 2014) and is used in clinical research (Cristache & Gurbanescu, 2017), but to our knowledge has not yet been validated.

The current non-invasive implant position assessments are indirect and rely on the accurate recording of the position of the ISB; however, this recording is also susceptible to measurement errors: inaccuracies here can result in a discrepancy between the recorded ISB position and the actual ISB position, which in turn leads to an erroneous estimation of the implant position (Figure 1c).

The aim of this paper is to develop and validate a new method, based on open-source software, which can be used to evaluate the accuracy of implant position assessment in partially edentulous patients using different techniques (conventional impression, intraoral scan, CBCT), when compared to a reference model obtained with an industrial scanner. The method relies on surface-based registration of a manufacturer-provided ISB three-dimensional (3D) model to the impression and has the potential to elude the limitations introduced by CBCT artifacts. It can potentially serve as a reference method in standardizing implant position assessment in future research.

2 | MATERIALS AND METHODS

Twenty-nine OsseoSpeed EV S 3.6×13 mm implants (Astra Tech Implant System, Dentsply Sirona Implants) were placed in four fresh frozen human cadaver heads (4 upper and 3 lower partially edentulous jaws, 13 implants in the anterior, and 16 in the posterior region).

The cadaver heads were provided by the Anatomy and Dissection Centre, and the study was approved by the Ethics Committee of UZ Leuven (University Hospitals Leuven) under study number NH019-2018-03-01. A summary of the study workflow is described in Figure 2.

2.1 | Surgical protocol

Based on pre-operative CBCTs and digital impressions (intraoral scans), tooth-supported surgical guides (Simplant SAFE®) were prepared using the Simplant Pro 18.0 (Dentsply Sirona Implants®) planning software. All implants were placed flapless and had a primary stability of ≥25 N cm.

2.2 | Data acquisition

Original open-tray impression copings (Implant Pick-Up EV, Long, ref. no. 26232, Astra Tech Implant System, Dentsply Sirona Implants) were inserted into the implants and hand torqued. Conventional impressions were taken using a regular-set medium viscosity polyether impression material (Impregum Soft, 3 M Oral Care, Seefeld, Germany) using an open-tray technique. The impression copings were removed, and ISBs (Atlantis® IO FLO, IO P-02, ref. no. 35244, Astra Tech Implant System, Dentsply Sirona Implants) were inserted and again hand torqued. A CBCT scan of the cadaver head was taken (NewTom VGi evo®, QR Verona) with the following settings: voxel size 0.15 mm, field of view (FOV) 10 × 10 cm, 110 kVp and 5.2 mA), using dry paper towels to separate the non-attached soft tissues (cheek, lip, tongue) from the teeth, scan bodies and gingiva around teeth and implants. Immediately afterwards, an intraoral scan was taken of all jaws (3shape Trios 3 Color, software: TRIOS 2015–1 build 1.4.7.5, 3Shape A/S, Copenhagen, Denmark). Finally, the jaws were removed from the cadaver heads (with the ISBs still in position) and scanned using an industrial scanner (GOM ATOS III Triple Scan 8 M, software: GOM ATOS Professional 2016, Carl Zeiss AG, Oberkochen, Germany). Casts were poured from the conventional impressions taken in the first step using type 4 stone (Fujirock EP Premium, GC Europe, Haasrode, Belgium), ISBs were inserted into the implant replicas, hand torqued, and then the casts were digitized using the same industrial scanner.

2.3 | Data analysis

2.3.1 | Three-dimensional measurements

The conventional impression (poured cast), intraoral scan, and industrial scan (used as the reference) resulted in 3D surface models. The CBCT resulted in a 3D volume which was segmented using Amira software (Amira 4.1, Thermo Fisher Scientific, Waltham, MA, USA) to obtain 3D surface models of the teeth and implants.

Three-dimensional models (STL files) of the implant and ISB were obtained from the implant manufacturer and surface-based registration using the iterative closest point (ICP) algorithm was performed (Besl & McKay, 1992). The translation and rotation needed to register an ISB from an impression to the reference ISB can be expressed as a transformation matrix, a rectangular array of numbers. These matrices were calculated for each ISB and each assessment technique, and each technique was then compared to the industrial scan, which served as a reference, to measure the deviation at implant shoulder and apex, as well as the angle of deviation. A more detailed description of the methodology and the source code for obtaining the measurements are provided in Supplementary Material 1.

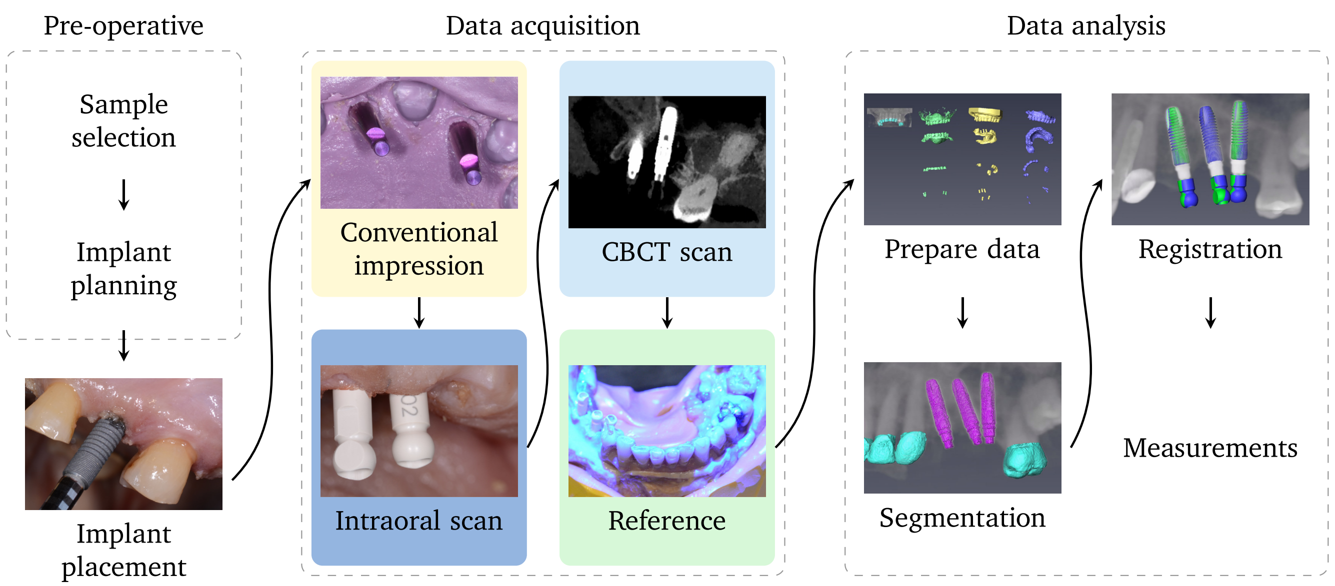

FIGURE 2 Summary of study workflow.

2.3.2 | Mesio-distal and bucco-lingual measurements

Measurements of the mesio-distal and bucco-lingual deviations were calculated using 3-Matic Software (Materialise, Leuven, Belgium). The following protocol was used: the implants resulting from the different acquisition modalities (CBCT, IOS, cast, industrial scan) were positioned in their respective coordinate system, with regard to the IOS of the cadaver's jaw. The latter was used as a reference to then section the implants from all four acquisition modalities in their center, following their mesio-distal and bucco-lingual axes (Figure 3).

The implant position acquired using the industrial scan was used as a reference. The sectioned implants from the CBCT, IOS and cast were then, respectively, superimposed on the one of the industrial scan, and 2D measurements of the mesio-distal and bucco-lingual deviations were performed. The mesio-distal and bucco-lingual planes are defined as orthogonal. The orientation of the mesio-distal plane was based on operator experience, and the corresponding bucco-lingual plane was obtained by rotating the view by 90° along the *Z* axis. Two measurements per implant were recorded: a coronal measurement at the level of the first thread under the shoulder of the implant – and an apical measurement at the level of the first apical thread of the implant.

2.4 | Statistical analysis

A weighted linear mixed model was created with site, nested in patient, as random factors, and assessment technique and anterior/posterior region as crossed fixed factors. Weights that were applied were inversely proportional to the value of the response variable. Multiple comparisons between assessments, and with the reference were corrected for simultaneous hypothesis testing according to Sidak. Assessments were always compared per region (anterior and posterior), and if no significant interaction was present, the averages of the anterior and posterior regions were also compared. The normal quantile plot of the residual values showed that a logarithmic transformation of the data was necessary.

3 | RESULTS

3.1 | Three-dimensional measurements

The descriptive statistics of the data are presented in Table 1 and the results of the statistical analyses in Table 2 and Figure 4.

3.2 | Deviation at implant shoulder

All assessments for the anterior as well as for the posterior implants had a statistically significant ($p < .01$) deviation compared to the industrial reference scan. For the anterior implants deviations of 0.13, 0.09, and 0.08 mm were recorded for CBCT, conventional impression and intraoral scan, respectively. For the posterior implants, the corresponding values were 0.11, 0.17, and 0.16 mm, respectively ($p < .01$). Because the interaction between anterior and posterior was statistically significant ($p < .01$), no analysis of the values averaged over anterior and posterior was performed. Between the 3 assessments, no significant differences were observed.

3.3 | Deviation at implant apex

Again, all assessments for the anterior as well as for the posterior implants had a statistically significant ($p < 0.01$) deviation compared to the industrial reference scan. For the anterior implants deviations of 0.16, 0.15, and 0.23 mm were measured for CBCT, conventional impression and intraoral scan, respectively. For the posterior implants, the corresponding values were 0.22, 0.25 and 0.38 mm, respectively.

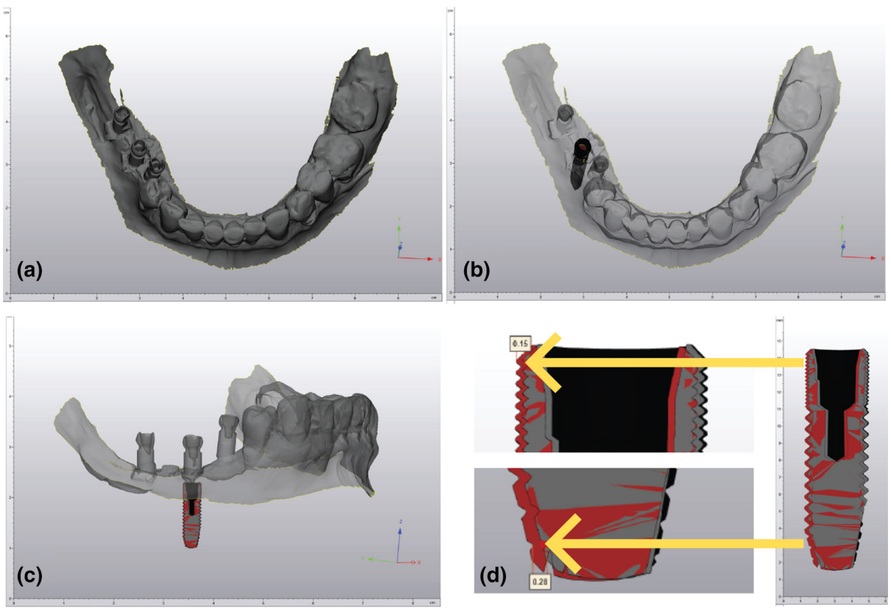

FIGURE 3 Based on the industrial scan of the arch (a), models from other imaging techniques were registered using the teeth (b, c), and implant position was determined using scan body registration. Implants were then sectioned along their center axis, according to their mesio-distal and bucco-lingual planes, to allow for coronal (at the level of the most coronal thread crest) and apical (at the level of the most apical thread root) measurements of the mesio-distal and bucco-lingual deviations (d).

TABLE 1 Deviations between different assessments and the industrial scan (mimicking the clinical situation).

	Deviation at shoulder (mm)			Deviation at apex (mm)			Deviation angle (degrees)		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
All implants									
CBCT	0.04	0.15	0.29	0.08	0.23	0.55	0.20	0.78	2.05
Conventional	0.06	0.17	0.44	0.05	0.25	0.74	0.08	0.73	1.80
Intraoral	0.03	0.18	0.70	0.13	0.45	1.15	0.18	1.29	3.71
Anterior implants									
CBCT	0.07	0.15	0.26	0.09	0.19	0.38	0.27	0.72	1.90
Conventional	0.06	0.10	0.21	0.05	0.19	0.35	0.13	0.63	1.17
Intraoral	0.27	0.11	0.19	0.13	0.34	1.00	0.18	1.12	3.65
Posterior implants									
CBCT	0.04	0.15	0.29	0.08	0.27	0.55	0.20	0.83	2.05
Conventional	0.06	0.22	0.44	0.12	0.30	0.74	0.08	0.80	1.80
Intraoral	0.05	0.24	0.70	0.15	0.53	1.15	0.34	1.43	3.71

Note: Measurements (minimum, mean, maximum) at implant shoulder, implant apex, as well as of the variation in implant angulation. Data for all implants, as well as for implants grouped by region (anterior/posterior).

TABLE 2 Statistical outcome for comparison between different assessment techniques and the industrial scan (mimicking the clinical situation).

	All measurements			Anterior			Posterior		
	Reference	Conventional	Intraoral	Reference	Conventional	Intraoral	Reference	Conventional	Intraoral
Deviation at shoulder (mm/*p*-value)									
CBCT				**.13**	.04	.05	**.11**	−.06	−.05
				< 0.01	.92	.52	<.01	.28	.53
Conventional				**.09**		.01	**.17**		.01
				<.01		1.00	<.01		.99
Intraoral				**.08**			**.16**		
				<.01			<.01		
Deviation at apex (mm/*p*-value)									
CBCT	**.19**	−.05	**−.12**	**.16**	.01	−.08	**.22**	−.03	**−.16**
	<.01	.34	<.01	<.01	1.00	.73	<.01	1.00	.02
Conventional	**.20**		**−.10**	**.15**		−.09	**.25**		−.12
	<.01		.02	<.01		.57	<.01		.19
Intraoral	**.30**			**.23**			**.38**		
	<.01			<.01			<.01		
Deviation angle (degrees/*p*-value)									
CBCT	**.66**	−.01	−.20	**.58**	.06	−.13	**.74**	.10	−.26
	<.01	1.00	.27	<.01	1.00	1.00	<.01	.99	.52
Conventional	**.58**		**−.28**	**.52**		−.19	**.63**		−.37
	<.01		.02	<.01		.91	<.01		.06
Intraoral	**.85**			**.71**			**1.00**		
	<.01			<.01			<.01		

Note: Deviation at implant shoulder was not analyzed for anterior and posterior implants combined, as the interaction between the two regions was statistically significant. Significant measurements are shown in bold.

The interaction between anterior and posterior data was not significant ($p = .36$), and the values averaged over anterior and posterior were 0.19, 0.20 and 0.30 mm, respectively. Moreover, the deviation for intraoral scans was significantly higher than for both CBCT (0.12 mm, $p < .01$) and the conventional impression (0.10 mm, $p = .02$).

3.4 | Deviation in implant angle

Considering the angle of deviation between the long implant axes, all 3 assessments deviated significantly ($p < .01$), for anterior as well as for posterior implants from the industrial reference scan,

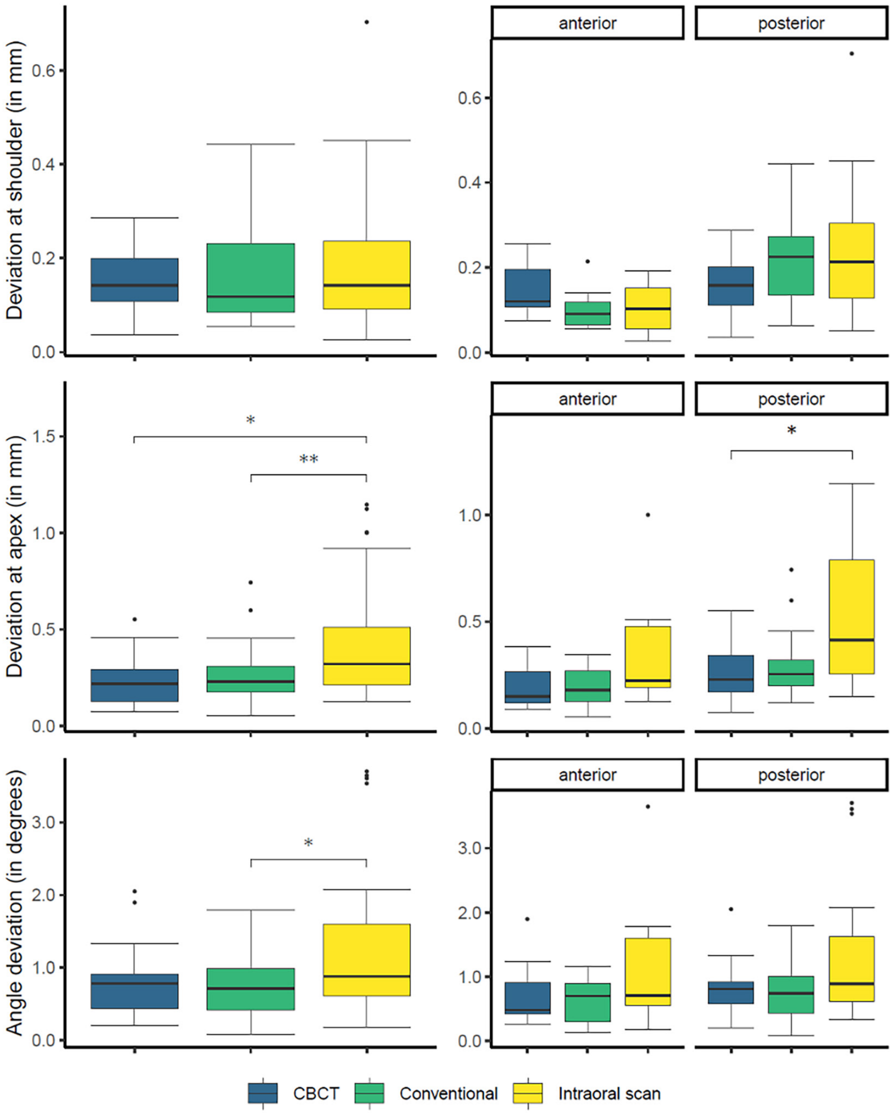

FIGURE 4 Three-dimensional deviations to reference scan per implant position assessment for all implants as well as per implant location (anterior/posterior). Deviations were measured at implant shoulder, at implant apex, and of the implant angle. *Statistically significant difference between assessment techniques.

with a deviation of 0.58° for CBCT, 0.52° for the conventional impression and 0.71° for the intraoral scan for anterior implants, and a deviation for posterior implants of 0.74°, 0.63° and 1.00°, respectively. No significant differences were identified between assessments.

As the interaction between anterior and posterior was not significant ($p = .20$), the angles were compared for the values averaged over anterior and posterior as well. The results were 0.66°, 0.58° and 0.85°, respectively ($p < .01$). With this analysis, the intraoral scan showed significantly higher deviations than the conventional impression technique.

3.5 | Mesio-distal and bucco-lingual measurements

The descriptive statistics of the data are presented in Table 3 and the results of the statistical analyses in Table 4 and Figure 5.

3.6 | Deviation at implant shoulder

All assessments for the anterior as well as for the posterior implants had a statistically significant ($p < .05$) deviation compared to the industrial reference scan. All deviations were below 0.10 mm. The interaction between anterior and posterior was not statistically significant ($p = .07$), so the statistical analysis was performed on all the implants in the dataset. There was no statistically significant difference between the tested methods.

3.7 | Deviation at implant apex

There was no statistically significant difference between the conventional impression and the reference scan ($p = .18$). All other assessments for the anterior as well as for the posterior implants had a statistically significant ($p < .05$) deviation when compared to the

TABLE 3 Mesio-distal (MD) and bucco-lingual (BL) deviations between different assessments and the industrial scan (mimicking the clinical situation).

	Deviation at shoulder (mm)						Deviation at apex (mm)					
	MD			BL			MD			BL		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
All implants												
CBCT	−0.19	−0.01	0.21	−0.19	0.02	0.19	−0.27	0.00	0.38	−0.32	0.02	0.36
Conventional	−0.32	−0.06	0.8	−0.31	−0.01	0.18	−0.56	−0.10	0.30	−0.28	0.00	0.48
Intraoral	−0.25	0.05	0.28	−0.67	0.03	0.45	−0.32	0.12	0.73	−0.88	0.04	0.78
Anterior implants												
CBCT	−0.19	−0.06	0.06	−0.19	0.00	0.19	−0.18	−0.09	0.03	−0.12	0.10	0.36
Conventional	−0.09	−0.03	0.04	−0.12	−0.02	0.05	−0.18	−0.07	0.03	−0.16	0.01	0.25
Intraoral	−0.06	0.02	0.22	−0.14	0.04	0.25	−0.18	0.08	0.55	−0.65	0.04	0.40
Posterior implants												
CBCT	−0.15	0.01	0.21	−0.19	0.02	0.18	−0.27	0.03	0.38	−0.32	−0.00	0.29
Conventional	−0.32	−0.06	0.8	−0.31	−0.00	0.18	−0.56	−0.12	0.30	−0.28	−0.00	0.48
Intraoral	−0.25	0.05	0.28	−0.67	0.03	0.45	−0.32	0.13	0.73	−0.88	0.04	0.78

Note: Measurements (minimum, mean, maximum) at implant shoulder and implant apex. Data for all implants, as well as for implants grouped by region (anterior/posterior). Positive values represent deviations towards the mesial and buccal directions, respectively, compared to the reference scan.

industrial reference scan. All deviations were less than 0.12 mm. The interaction between anterior and posterior was not statistically significant ($p = .98$), so the statistical analysis was performed on all the implants in the dataset. There was no statistically significant difference between the tested methods.

4 | DISCUSSION

There was a statistically significant difference between the reference (industrial scan), and all other assessments. With regards to the position of the implant apex and the angle of deviation, CBCT accuracy was comparable with conventional impressions, while the intraoral scan showed both more deviation at the apex, as well as more angle deviation. When looking at posterior implants, deviation at the apex was almost twice as large for the intraoral scan than for CBCT (mean difference 0.38 vs. 0.22 mm).

Several recent studies have investigated the accuracy of intraoral scanners under different conditions. Partially edentulous arches with short edentulous seem to result in higher accuracy (Abduo & Elseyoufi, 2018; Fattouh et al., 2021; García-Gil et al., 2020). Digital impressions taken of the posterior region also seem to be more inaccurate (Moon & Lee, 2020; Sun et al., 2018). There also seem to be large differences between different scanner models (Amornvit et al., 2021), especially for more demanding applications, such as when scanning complete arches (Ender et al., 2019; Treesh et al., 2018). Full-arch impressions of oral implants have also long represented a challenge (García-Gil et al., 2020; Zhang et al., 2021), although a recent systematic review suggests that current scanners may be reaching clinically acceptable levels of accuracy (Schmidt et al., 2022). Ender and Mehl (2015) found that both trueness and precision are higher for conventional impressions (11.5 and 14.6 μm, respectively) when compared to digital (different scanners were tested and ranged between 29.4–44.9 and 19.5–63 μm, respectively).

A recent systematic review showed that digital implant impressions have similar accuracy when compared to conventional impressions of partially edentulous arches, but that the accuracy of digital impressions seems to be better when using angulated implants (Flügge et al., 2018). Most of these findings are based on in vitro studies, and in vivo studies usually do not provide a reference measurement when comparing impression techniques (Wismeijer et al., 2018). A recent study was able to overcome this limitation by using an industrial scanner in vivo, but only for the anterior and premolar regions (Nedelcu et al., 2018). They did not find a significant difference between conventional and digital impressions, suggesting the technology is improving.

In the present paper, we introduce a novel technique which allows the ex vivo comparison of various impression techniques with a reference for both the anterior and posterior region of the dental arch. A reference 3D model was used and calculations were performed using transformation matrices, using all points of the model rather than a limited number of observer measurements. We focus on scan bodies and implants in this experiment, but the technique can similarly be applied to any surface for which a reference 3D model is available (e.g. orthodontic brackets, prosthetic abutments, etc.). The authors believe this method may have the potential to enable more accurate measurements between compared to traditional (mesio-distal and bucco-lingual) linear measurements, as it does not

TABLE 4 Statistical outcome for comparison between mesio-buccal and disto-lingual deviations between different assessment techniques and the industrial scan (mimicking the clinical situation).

	All measurements			Anterior			Posterior		
	Reference	Conventional	Intraoral	Reference	Conventional	Intraoral	Reference	Conventional	Intraoral
Deviation at shoulder [mm/*p*-value]									
CBCT	**.06**	.00	.00	**.05**	.00	.01	**.06**	.01	−.01
	0	.98	1.0	<.01	1	.99	0	1.0	1.0
Conventional	**.05**		−.00	**.05**		.01	**.06**		−.01
	0		1.0	<.01		1.0	0		.91
Intraoral	**.05**			**.04**			**.07**		
	0			.02			0		
Deviation at apex [mm/*p*-value]									
CBCT	**.09**	.02	−.02	**.08**	.02	−.01	**.09**	.01	−.03
	0	.69	.58	.01	.92	1.00	0	1.00	.51
Conventional	**.07**		−.04	.05		−.04	**.09**		−.04
	<.01		.09	.18		.71	0		.25
Intraoral	**.10**			**.09**			**.12**		
	0			<.01			0		

Note: Positive values represent deviations towards the mesial and buccal directions, respectively, compared to the reference scan. Significant measurements are shown in bold.

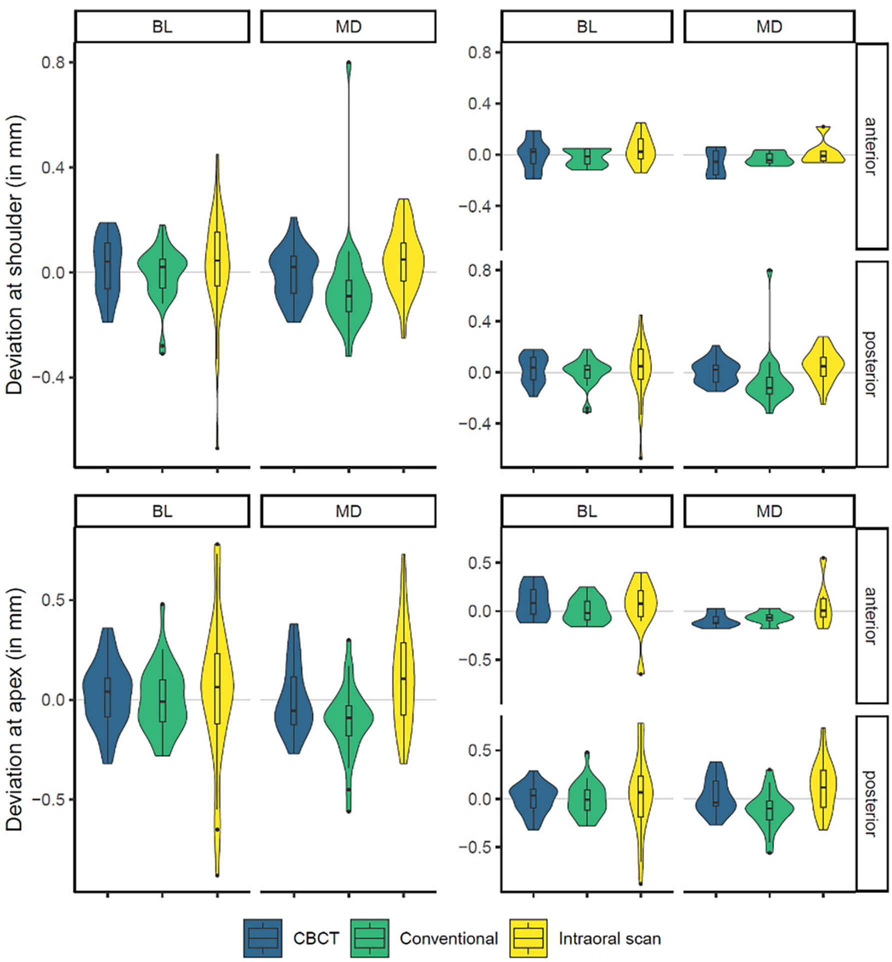

FIGURE 5 Bucco-lingual (BL) and mesio-distal (MD) deviations to reference scan per implant position assessment for all implants as well as per implant location (anterior/posterior). Positive values represent deviations towards the mesial and buccal directions, respectively, compared to the reference scan. Measurements were performed at implant shoulder and implant apex.

rely on the observer selecting corresponding points on different models, but rather uses the position of the models themselves in three-dimensional space to determine the deviation mathematically. This aspect becomes increasingly important when dealing with sub-millimeter resolutions, as is the case in most contemporary studies.

Our results confirm previous findings that the inaccuracy of intraoral scanners is higher in the posterior region, most likely due to limited access to this region. While these findings are relevant, they must also be looked at from the perspective of clinical relevance. For several applications (anterior region, single crowns, short edentulous spans), the accuracy of the intraoral scanner may be good enough, while for others the conventional impression and CBCT (larger edentulous spans, complete or fully edentulous arches) may still provide a clinical advantage (Rasaie et al., 2021; Zhang et al., 2021).

Another important aspect to consider is that implant length also plays a role in the amount of deviation at apex observed. All implants used in this study had a length of 13 mm, which is relatively long and amplifies the measurement error. Given that most studies about surgical guide accuracy report deviations at the apex of more than 1 mm (Van Assche et al., 2012), positions determined with an intraoral scanner may still be relevant.

Although we attempted to reproduce the clinical environment to the best of our ability, this study does suffer from some limitations. It is an ex vivo study, and therefore the intraoral conditions were different than in a living patient (saliva, breathing and temperature differences, which may cause fogging, were absent). These conditions may actually have been favorable for the posterior region when using the intraoral scanner, which may further enhance the relevance of the results. The protocol itself is based on open-source tools, but does require the availability of manufacturer-supplied ISB and implant 3D model. We believe the solution should be to encourage manufacturers to provide these models for research purposes, as was the case here. Furthermore, we used a specific intraoral scanner (3shape® Trios 3 Color) in this study, but the literature suggests that there may be large quality differences between different intraoral scanner models, similar to the situation encountered with cone-beam CT devices (Jacobs et al., 2018). The situation is similar with ISBs, where design and material seem to have a major impact on accuracy (Marques et al., 2021; Mizumoto & Yilmaz, 2018). Another limitation of our study is that we did not investigate deviations in depth measurements, a common measurement in such studies, however the method should be extensible to include these measurements. Finally, the software version may potentially also have an impact on accuracy, as these systems are closed and the impact of software updates is unclear, potentially resulting in reproducibility issues.

Further research could expand on the method described here to implement a fully open protocol for assessing guided surgery accuracy (meaning planning/guide design should also be performed using open tools). For some applications, examining deviations along a specific direction (e.g. along the mesio-distal direction) could also provide additional value.

5 | CONCLUSION

All assessment methods were less accurate than the reference industrial scan. Intraoral scans were less accurate when determining the implant position in the posterior region than both conventional impressions and CBCT. Depending on the application, however, this inaccuracy may be clinically insignificant, making them a valid alternative for non-invasive implant position assessment.

AUTHOR CONTRIBUTIONS

Marc Quirynen and Mihai Tarce conceived the idea for this study. Mihai Tarce and Kathrin Becker collected and analyzed the data. Pierre Lahoud assisted with the data analysis. Reinhilde Jacobs and Sohaib Shujaat set up and supervised the medical imaging (CBCT) data acquisition. Mihai Tarce and Marc Quirynen led the writing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest. Dentsply Sirona Implants kindly provided the implants, implant guides and surgical sets necessary to perform this study, as well as access to the industrial scanner.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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