RESEARCH AND EDUCATION

Accuracy analysis of complete-arch digital scans in edentulous arches when using an auxiliary geometric device

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ABSTRACT

Statement of problem. Obtaining reliable digital scans of edentulous patients is challenging because of the absence of anatomic landmarks/geometric variations along the dental arch. Whether adding an auxiliary geometric device (AGD) will improve scanning is unclear.

Purpose. The purpose of this in vitro study was to analyze the accuracy of complete-arch digital scans of completely edentulous arches by placing a consumable AGD.

Material and methods. A stainless-steel model of the maxilla of a completely edentulous arch with 4 implants was built. The model was scanned with a reference industrial scanner as the control and with 3 intraoral scanners (True definition, Trios 3, iTero). Each intraoral scanner was used 10 times without the AGD in place and 10 more times with the AGD fixed on the model. Accuracy in terms of trueness and precision was established by comparing 5 reference distances with or without the AGD in place. Software for analyzing 3-dimensional (3D) data was used to measure these 5 distances and data analysis software was used for statistical and measurements analysis (α=.05).

Results. Significant differences (*P*<.05) were found in all reference distances for trueness and in 4 of the 5 reference distances for precision depending on whether the AGD had been used. Without the AGD in place, trueness ranged from 21 ±16 µm in the shortest reference distance to 125 ±80 µm in the largest reference distance. With the AGD in place, trueness ranged from 11 ±8 µm in the shortest reference distance to 64 ±51 µm in the largest reference distance. Precision ranged from 18 ±14 µm in the shortest to 84 ±74 µm in the largest reference distance without the AGD and from 7 ±7 µm in the shortest to 63 ±46 µm in the largest with it.

Conclusions. Complete-arch digital scans of edentulous jaws are more accurate when an AGD is used to resolve the lack of anatomic landmarks. An additional advantage is that the use of the AGD allows for a more fluent scanning process.

CLINICAL IMPLICATIONS

The accuracy of complete-arch digital scans of edentulous patients can be improved with the use of an easy-to-fabricate device. Therefore, the passive fit of structures fabricated from these scans is improved and better prostheses can therefore be provided.

INTRODUCTION

The digital workflow begins in the oral cavity with intraoral scanners. These scanners provide digital scans from which structures or prostheses are fabricated. For implant-supported restorations, the validity of digital scans will be determined in part by how they fit into the dental implants. Accuracy is necessary to obtain a passive fit between the superstructure and implants.[1,2] Although passive fit has been analyzed in various studies, an agreed value for the limits of passive fit is lacking.[3-5] Lack of accuracy can lead to mechanical failures in an implant-supported prosthesis[6,7] or biological complications in the surrounding tissues.[3] Some research studies have evaluated small areas that simulate a crown or fixed partial denture[8-14] and others evaluated larger areas simulating a quadrant restoration[15] or complete-arch restoration.[16-26] The methodology used in these studies to assess accuracy, trueness, or precision of intraoral scanners has differed. However, they indicate that the accuracy of dental scans is better than, or at least as good as, the accuracy of conventional impressions, when the scanned area is small, up to a quadrant.[8-11,14,15] In addition, obtaining accurate digital scans of the arch where there are large homogeneous areas, such as the spaces between implants in edentulous arches, is especially difficult.[22,27-29]

Obtaining reliable digital scans of edentulous arches can be challenging, even impossible.[27-29] These difficulties are due to the absence of anatomic irregularities in the area to be scanned. Also, when the scanner images scan bodies, placed specifically to obtain an accurate digital scan, the identical geometry (usually with most of the surfaces being cylindrical) can cause interpretation errors. The scanner can confuse the different scan bodies, interpreting them as only one.[27] Andriessen et al[27] reported that most digital scans of edentulous arches with 2 scan bodies were unusable. The distance between implants also influences the accuracy of the digital scan so that the longer the distance with a uniform surface, the more challenging the scanning process.[22,29]

These problems reflect difficulties of intraoral scanners in joining multiple images captured during the scanning process.[24] The software of the intraoral scanners builds the 3-dimensional (3D) images of the dentures by best-fit alignment of the images made with the camera. The acquisition of larger areas is more challenging and software algorithm processes are more complex.[24] But regardless of the area to be scanned, the lack of differences in the radius of curvature in the geometry of an edentulous patient also creates difficulties. The geometric and color differences (depending on the technology used) that scanners find in the joining process facilitate this process and the lack of these characteristics in the oral cavity of an edentulous patient constitutes its singularity.[27,29,30] This aspect means that digital scanning of edentulous arches is one of the hardest tasks in these patients.

Stereophotogrammetry technology (PIC Camera; PIC DENTAL) has addressed this problem by using an extraoral camera. Specific targets (PIC Abutments; PIC DENTAL) are placed in as many abutments as implants in the oral cavity and the extraoral camera captures their position. This camera provides a standard tessellation language (STL) file where the abutments are highly accurately positioned.[3,31] Accurate dental digital scans are then built by combining this STL file with another STL file obtained from an intraoral scanner.

The purpose of this in vitro study was to determine if the dental conditions influence the accuracy of digital scans. Differences in measurement errors were compared with an edentulous and dentate model. Then, to address the lack of anatomic landmarks, this study used the auxiliary geometric device (AGD) described by Iturrate et al,[32] to determine if more accurate digital scans of edentulous arches could be obtained. This goal, unlike with stereophotogrammetry, can be achieved with a single intraoral scanner. The null hypothesis was that there are no significant differences between the accuracy of digital scans acquired with or without the AGD.

MATERIAL AND METHODS

A stainless-steel model was fabricated, based on the maxilla of an edentulous patient. The model contained 4 cylinders machined to simulate 4 scan bodies. The position of each cylinder corresponded to that of maxillary right third molar, maxillary right canine, maxillary left canine, and maxillary left third molar (Fig. 1A).

The stainless-steel model was scanned 10 times with a blue light-technology industrial reference scanner (ATOS Compact Scan 5M/300; GOM) as a baseline. A highly accurate scanning protocol was used and 10 STL files were obtained.

The stainless-steel model was also scanned 10 times, in 2 different scenarios, with 3 different intraoral scanners, resulting in 60 STL files (20 STL files with each intraoral scanner). The scanners used were Trios3 (3 Shape A/S) with 2015-1 software version, True Definition

(3M ESPE) with 5.1.1 software version, and iTero (Align Technology Inc.) with 1.5.0.361 software version. In the first scenario, 10 scans of the edentulous model were made with each of the 3 intraoral scanners (n=30), as done clinically. In the second scenario, an AGD was placed and luted to the stainless-steel reference model with light-polymerizing resin (CONLIGHT; Kuss Dental) (Fig. 1B). Subsequently, 10 new scans were made with each scanner (n=30). The AGD was designed to simulate a conventional complete-arch denture and later prototyped on a 3D printing machine (Dimension Elite; Stratasys) using acrylonitrile butadiene styrene (ABS Plus). ABS is a common nontoxic thermoplastic polymer. Among other features, it is opaque and appears on the scan.

All the scans were made according to the manufacturer's scanning protocols for a complete arch. With the Trios3 and Itero, the scanning began in the right first molar, and when using the True Definition, in the right canine. To perform the scans with True Definition, the model was powdered (Lava COS Powder; 3M ESPE) as is done in clinical practice. All scans (n=60) were performed by the same person (M.I.), in the same location, and under the same humidity and temperature conditions. The data files were directly exported as STL files with Trios, or post-processed and downloaded as STL files from specific clouds with True Definition and Itero (Fig. 1C, D).

As a result of this double scan, 2 groups of digital scans were obtained. The group achieved with the AGD (agdY group) presumably offering an accurate position of the scan bodies but lacking the soft tissues (Fig. 1D), while the group achieved without the AGD (agdN group) showed the soft tissues surrounding the scan bodies but presumably had a higher positioning error of those scan bodies (Fig. 1C)

Five reference distances were defined by linking 4 points located in each mechanized cylinder (D12, D13, D14, D23, and D34) (Fig. 2A). These reference distances were created with 3D inspection and mesh-processing software (GOM Inspect; GOM) in each STL file (70 STL files). The 4 points in each mesh were created following a highly accurate measurement protocol: each one was defined as the intersection between a cylinder axis and a plane created on each part of the mesh resembling a cylinder (Fig. 2B). The 4 cylinders created on each mesh were defined according to the Gaussian best-fit method. The software squared the deviations of the selected polygons to the possible fitting element and added up the quadratic deviations. For that selection of polygons, the 3-sigma distribution was used, which represented approximately 99.7% of all polygons. To create the intersection planes, the upper surface of each cylindrical part of the mesh was selected by the software, considering the mathematically-useful surface. After this, and again following the Gaussian best-fit method and 3-sigma polygon selection (approximately 99.7% of all polygons), the planes were created. By intersecting the created cylinders with the planes, 4 points were created in each of the cylindrical parts of the mesh. By joining these 4 points, the 5 reference distances were created (D12, D13, D14, D23, and D34).

The gold standard was assessed as the mean of the measurements in each reference distance from the STL files obtained with the reference scanner (ATOS Compact Scan 5M/300). The same 5 reference distances were measured in each of the 60-scan data obtained from the intraoral scanners (300 measurements) differentiating the 2 groups (agdN, agdY). The measurements were made with 3D inspection and mesh-processing software (GOM Inspect; GOM)

The distance data were imported into a statistical program (IBM SPSS Statistics v24; IBM Corp). Accuracy was evaluated in terms of trueness and precision. To assess trueness values in each reference distance, the mean deviation from the control and the standard deviation in each measured distance were used. Precision was evaluated as deviation of each measurement from the mean value of measurements in each reference distance, so both mean and standard deviation of precision were assessed (α=.05).

To compare the influence of the AGD on accuracy, the evaluation was performed twice: once with the AGD in place and fixed on the model (agdY), and once without the AGD on the stainless-steel model (agdN). The evaluation was performed by comparing in each reference distance the differences between measurements obtained from the STL files from the intraoral scanners and the control measurements.

The digital complete-arch scans were then created by combining 2 STL files and following a specific technique.[32] One STL file was obtained from agdY group and the other from agdN group. Firstly, a virtual partition of the digital scan of the edentulous jaw without the AGD was made by splitting the mesh into as many parts as there were scan bodies (Fig. 3). Then the AGD was digitally erased from the scan of the edentulous jaw (Fig. 4). Finally, each split part obtained from the partition of the first data file was aligned with the corresponding scan body from the second data file, thus achieving a complete-arch digital scan of an edentulous jaw (Fig. 5).

RESULTS

After the data analysis, precision and accuracy results were obtained by comparing 2 scenarios: an edentulous jaw and a dentate jaw (simulated by placing the AGD on the model). After measuring the 10 STL files provided with the reference scanner, the gold standard in each reference distance was assessed: 22.401 mm for D12; 42.290 mm for D13; 44.528 mm for D14; 31.060 for D23; and 22.970 mm for D34.

For the precision and independent of the scanner, the Levene test showed statistically significant differences (P<.05) in D12, D13, D14, and D34 reference distances and no significant differences (P>.05) in D23, depending on whether the AGD had been used. As Table 1 and Figure 6 show, precision mean values varied from 18 ±14 µm without the AGD to 7 ±7 µm with the AGD in D12 reference distance; from 47 ±35 µm to 32 ±24 µm in D13 reference distance; from 84 ±74 µm to 63 ±46 µm in D14 reference distance; from 38 ±28 µm to 21 ±18 µm in D23 reference distance; and from 22 ±17 µm to 8 ±7 µm in D34 reference distance. Precision values improved in all reference distances. In addition, Table 1 and, especially, Figure 7 show that the magnitude of these reference distances also influenced the obtained precision values. The larger the distance to be measured, the less accurate these measurements.

Concerning trueness, results were also stated regardless of the used scanner. The *t* test for the equality of measurement showed statistically significant differences (P<.05) in 5 evaluated reference distances (D12, D13, D14, D23, and D34) depending on whether the AGD had been used. Trueness in all evaluated distances (D12, D13, D14, D23, and D34) improved when the scans had been provided using the AGD. Trueness varied in D12 reference distance from 21 ±16 µm without the AGD to 11 ±8 µm when the scans where provided with AGD; from 65 ±40 µm to 33 ±26 µm in D13 reference distance; from 125 ±80 µm to 64 ±51 µm in D14 reference distance; from 47 ±39 µm to 20 ±21 µm in D23 reference distance; and from 38 ±29 µm to 18 ±12 µm in D34 reference distance. Table 2 shows the maximum and minimum (CI 95%), mean, and standard deviation of trueness and Figure 8 shows the deviation from reference distances. As with the precision analysis, the magnitude of reference distances also influenced the obtained precision values: trueness decreased with an increased reference distance. Figure 9 shows the distance-dependent deviation change.

DISCUSSION

Based on the results, the null hypothesis that there are no significant differences between the accuracy of intraoral scans obtained with or without the AGD was rejected. The present study showed that the absence of anatomic irregularities in large spaces, such as those found in edentulous arches, has a negative influence on the accuracy of dental digital scans. These findings are consistent with studies that reported the difficulty of obtaining dental digital scans of edentulous arches and how the lack of anatomic irregularities, or the presence of large homogeneous areas between anatomic landmarks, adversely affects the process of best-fit union performed by intraoral scanners.[22,27-29]

Consistent with the analysis performed by Kim et al,[28] an auxiliary device provided a solution to the lack of anatomic irregularities, giving the scanner a greater number of spaces with curvature radius changes for its best-fit joining process. In the present study this auxiliary device simulated a denture. After placing and fixing it in the mouth, it helped the scanner in the process of generating the 3D image, thus creating a more accurate digital scan.

Trueness and precision values of the measurements were compared among the data files achieved from digital scans obtained firstly with the AGD in place and then without. The analysis demonstrated that the use of the AGD helped to improve scanning results (Tables 1, 2).

Nevertheless, improvement does not necessarily imply the clinical validity of scans obtained when using an AGD. Studies have evaluated the maximum value of passive fit of structures in the mouth and although there is no generally accepted value, some reported maximum acceptable errors of between 95 µm and 150 µm.[4,5] The accuracy values found in this study show that trueness varied from 11 ±8 µm to 64 ±51 µm when using the AGD, whereas when this device was not used, it ranged from 21 ±16 µm to 125 ±80 µm. Based on the related studies, it could be argued that the use of the AGD would ensure a good structure–abutment passive fit. However, it must be considered that these values refer to mean values and the scanning results approach the limit values. Therefore, a single scan result could exceed the recommended maximum value for passive fit.

These limited values for both trueness and precision were given at the larger reference distance (D14). Therefore, to a certain extent, they support conclusions reached by authors related to the accuracy of intraoral scanners: digital scans are highly accurate in prostheses that restore small spaces, such as crowns and fixed partial dentures, but where the length of the arch to be restored is extensive, the suitability of digital scans is more questionable.[8-12,15,18-27]

Once that the AGD placed on the dental arch was demonstrated to provide a more accurate position of the scan bodies, and consequently of the implants, it was necessary to build a complete digital scan of the edentulous arch. For this purpose, similar to the solution with stereophotogrammetry (PIC Camera; PIC DENTAL), the 2 STL files were combined, using the information each provided: digital scans made with the AGD in place, supplying an accurate position of the scan bodies; and digital scans without the AGD, showing the soft tissues surrounding these scan bodies.

The results of this study show that it is possible to obtain reliable digital scans of edentulous arches by using a specific technique.[32] The technique provides a solution to a challenging situation in prosthetic dentistry, that of restorations in completely edentulous arches. The results were analyzed considering only the influence of the AGD and without considering the very likely different results between different intraoral scanners. The use of powder with only one of the scanners may also affect the results as well as the use of a metal-based model which sometimes cause problems with optical devices.[33] Both the design of the AGD and its fabrication are straightforward, and it can be easily integrated in the processes, even in devices or software that are already used. It is a technique that can be used with any intraoral scanner.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. Regardless of which intraoral scanner is used, accuracy values were worse in jaws with edentulous areas.
2. The use of an AGD covering such homogeneous areas as those found in edentulous arches enables intraoral scanners to obtain more accurate digital scans.
3. Both trueness and precision values were significantly improved.
4. The interference that the AGD can generate in 3D images when designing a structure can be solved by combining this image with an additional one obtained with the same intraoral scanner and using mesh-processing software.

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TABLES

Table 1. Precision of measurements with or without AGD (µm)

Precision	CI 95% Min.	CI 95% Max.	Mean ±SD
P12_N	13	24	18 ±14
P12_Y	4	10	7 ±7
P13_N	34	60	47 ±35
P13_Y	23	41	32 ±24
P14_N	56	111	84 ±74
P14_Y	45	80	63 ±46
P23_N	27	48	38 ±28
P23_Y	14	27	21 ±18
P34_N	16	28	22 ±17
P34_Y	5	10	8 ±7

AGD, auxiliary geometric device; CI, confidence interval; N, without AGD; P, precision; SD, standard deviation; Y, with AGD.

Table 2. Trueness of measurements with or without AGD (µm)

Trueness	CI 95% Min.	CI 95% Max.	Mean and SD
T12_N	15	27	21 ±16
T12_Y	8	14	11 ±8
T13_N	50	80	65 ±40
T13_Y	24	43	33 ±26
T14_N	95	155	125 ±80
T14_Y	45	83	64 ±51
T23_N	33	62	47 ±39
T23_Y	12	28	20 ±21
T34_N	27	49	38 ±29
T34_Y	13	22	18 ±12

AGD, auxiliary geometric device; CI, confidence interval; N, without AGD; P, precision; SD, standard deviation; Y, with AGD.

FIGURES

Figure 1. Reference model and digital scans. A, Stainless-steel reference model. B, Stainless-steel reference model with AGD placed and fixed. C, Digital scan of reference model. D, Digital scan of reference model with AGD. AGD, auxiliary geometric device.

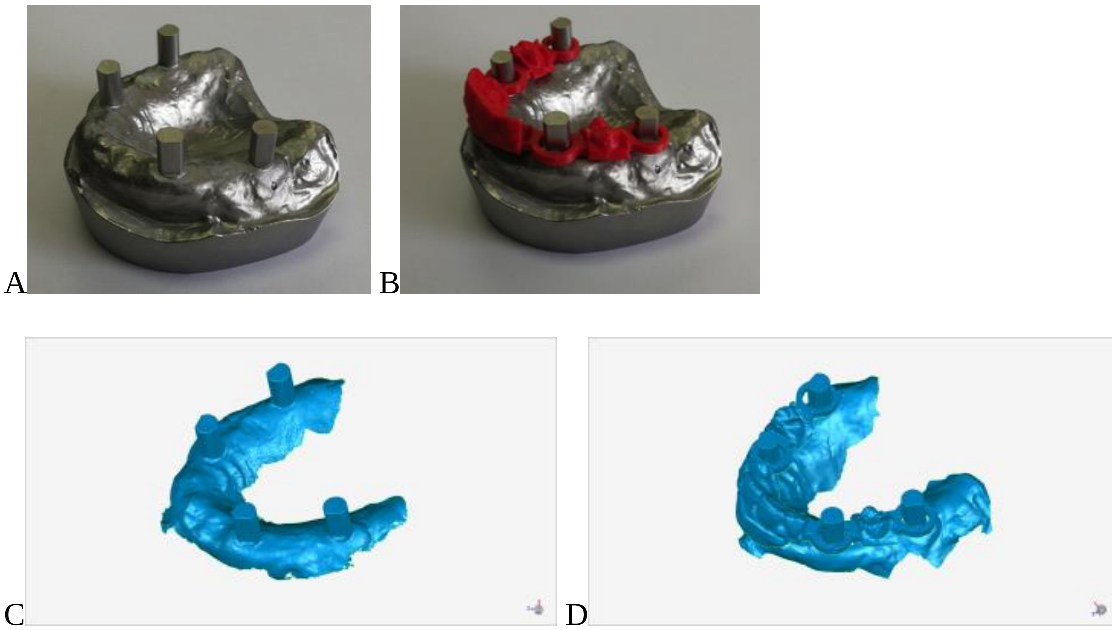

Figure 2. Obtaining reference distances. A, Five evaluated reference distances. B, Reference point construction with GOM Inspect.

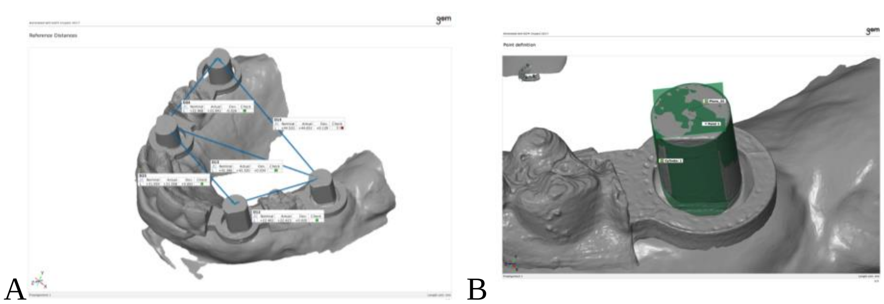

Figure 3. Virtual partition of digital scans.

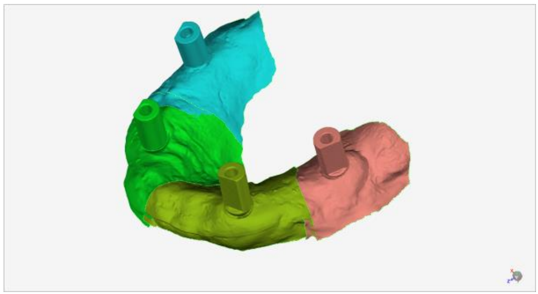

Figure 4. Erasing AGD.A, Surface of digital scans to be removed highlighted in red. B, Scan bodies accurately positioned after virtual AGD removal. AGD, auxiliary geometric device.

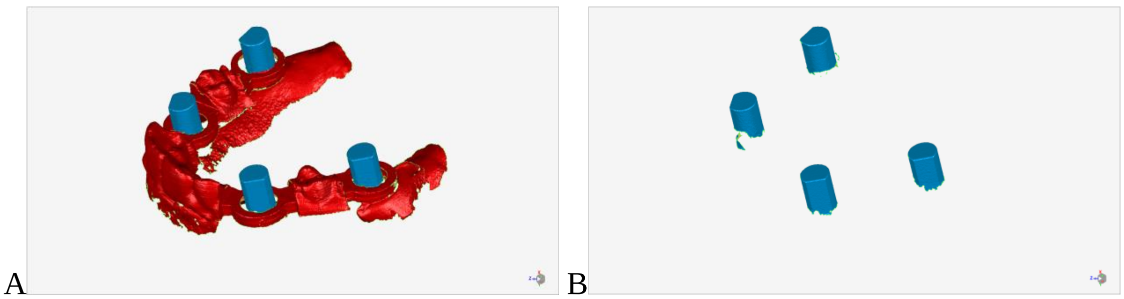

Figure 5. Construction of digital scan. A, Aligning first split part. B, Aligning second split part. C, Aligning third split part. D, Aligning fourth split part.

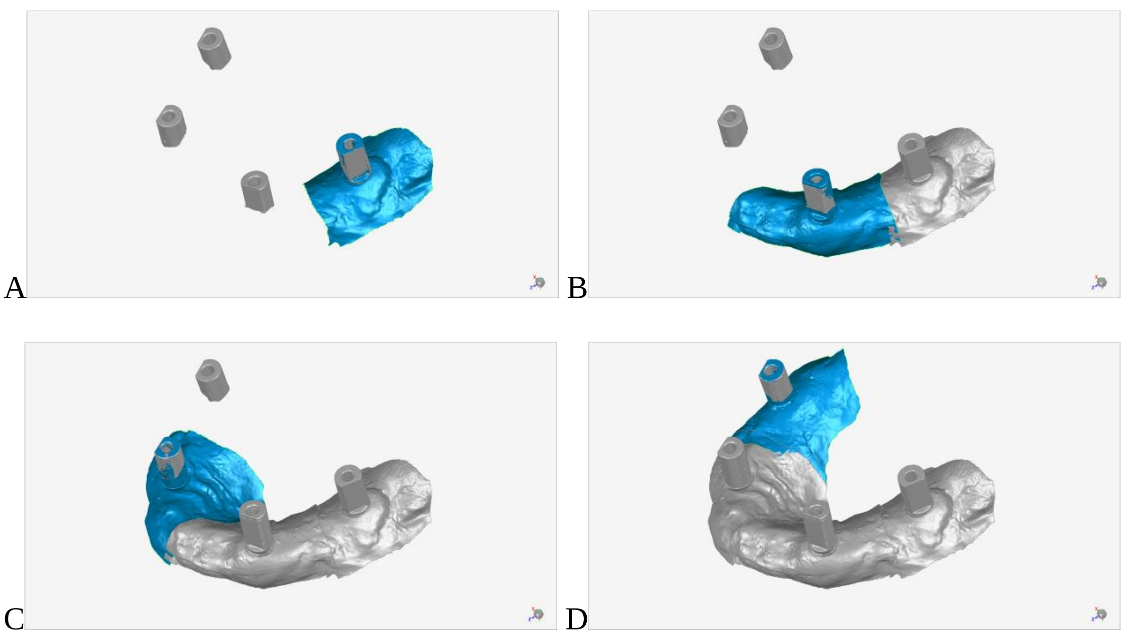

Figure 6. Precision of distance measurements with or without AGD. AGD, auxiliary geometric device.

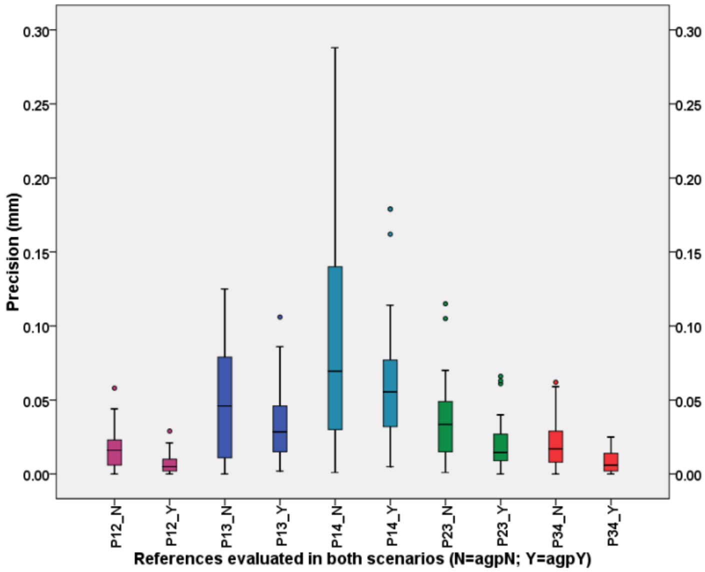

Figure 7. Precision in each reference distance.

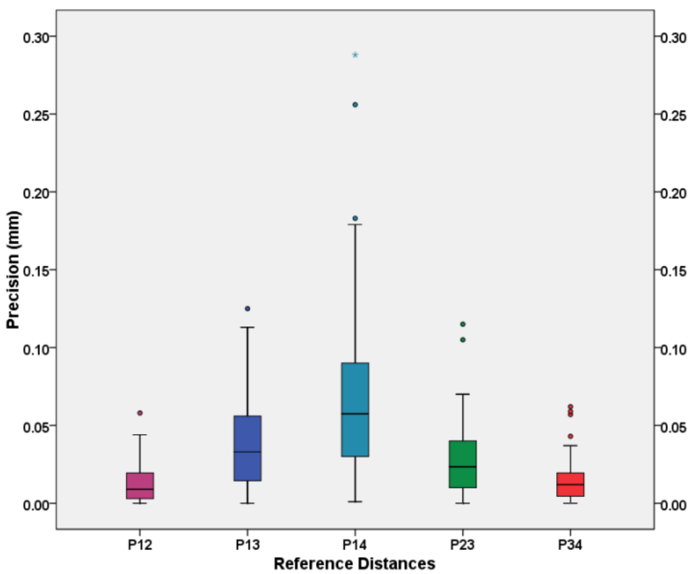

Figure 8. Deviation of measurements with or without AGD. AGD, auxiliary geometric device.

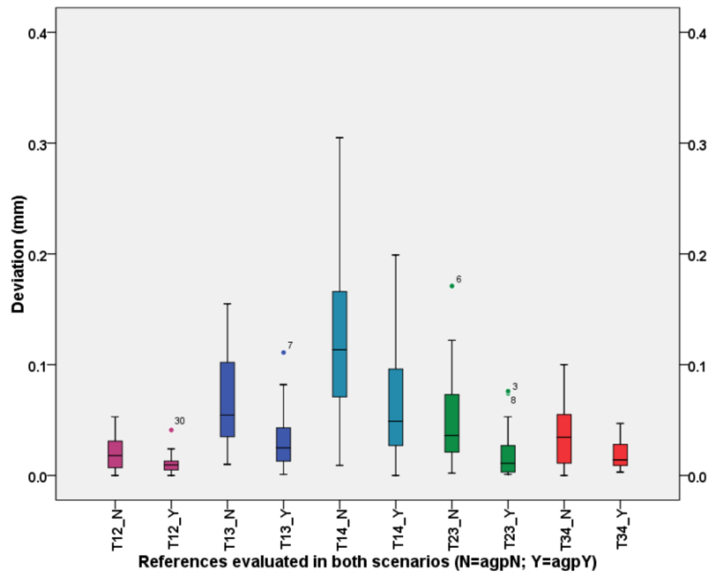

Figure 9. Deviation of measurements depending on reference distances.