



Photogrammetry as an alternative for acquiring digital dental models: A proof of concept



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ABSTRACT

Photogrammetry is a mathematical technique that generates three-dimensional coordinates of specific points identified from multiple images of the same object obtained at different angles. This technique may be a low-cost alternative for traditional scanning. The objective of this proof of concept was to evaluate the accuracy and precision in obtaining digital models (DM) from a plaster model (PM) using photogrammetry. Five DM were generated from 50 photographs taken surrounding the PM. The photographs were taken by a single operator on five consecutive days using natural light. The images obtained were processed on 3DF Zephyr Free software. The height and width of all teeth were recorded on both PM and DM, as well as the distance between the canine cusps (C–C) and between the mesiobuccal cusps of the first molars (1 M–1 M). For the PM the measurements were taken with a digital caliper, whereas the DM was measured using the software Blender. The DM and PM measurements presented a limit of agreement between -0.433 and 0.611 mm. The accuracy of DM measurements showed a SD of ± 0.171 mm and a repeatability coefficient of 0.474 . In the superimposition of all DM, it was possible to notice a greater discrepancy in the posterior region of the arch and palate, but this difference decreased when the region was segmented. It can be concluded that photogrammetry appears to be a viable technique for the digitization of dental models. Further studies need to be performed to evaluate its clinical application.

Introduction

In the last decades of the last century, computing and the internet revolutionized the manufacture process, which was defined as the Third Industrial Revolution [1]. As a direct result of this progress, we are now amid the Fourth Industrial Revolution. The main characteristic of this era is breaking of the border that distinguishes the physical and digital domains, allowing the creation of cyber-physical systems [2]. As this revolution is not restricted to the large scale means of production, reverberations of this phenomenon are noticed in all professions with the improvement of old processes and the emergence of new technologies that interchange between the physical and digital. In this way, faster, more precise and standardized processes have been increasingly taking the space once occupied by traditional techniques. In dentistry this can be noticed by the increasing incorporation of a digital approach in the diagnosis, planning and execution of treatments [3–5].

With the digital incorporation into clinical practice, dentists can add greater predictability with less chair time at their treatments. This

practice is increasingly present in restorative treatments [5], in implant planning and placement [3] and for major surgeries [6]. The common aspect to all these techniques is the need of converting a real object into a digital, and there are some alternatives for this process. Although the use of computed tomography is indicated for bone reconstruction [6], there are more adequate ways of reproducing dental and oral structures without exposing the patient to radiation, such as 3D scanning [5,7]. With the use of dental scanners it is possible to obtain digital records with high precision and accuracy, being similar or superior to traditional impressions in some cases [7]. However, the high price of the equipment can still be an impediment factor for dentists, restricting the digital introduction in their clinics. For this reason, it is interesting to develop low-cost techniques such as photogrammetry.

Photogrammetry is a mathematical technique based on the generation of three-dimensional coordinates to define the spatial arrangement of an object by identifying repeated points in multiple images acquired at different angles of the same object [8–10]. This technique has been used with great reliability in scientific studies, such as

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evaluation of the growth of biological samples in culture media [11], development of plant structures [12,13] and for obtaining medical parameters from patients [14–17]. In the field of dentistry, photogrammetry has already been used to obtain digital models by taking intraoral [10,14] and extraoral images [18], and is also a very useful tool in the planning and evaluation of results of maxillofacial surgeries by providing a good registry of soft tissues [19,20].

The hypothesis

Photogrammetry is a potential low-cost alternative for acquiring digital models compared to dental scanners. The objective of this proof of concept was to evaluate the accuracy and precision of photogrammetry as a practical and cheaper alternative for digitizing plaster models, providing a more accessible introduction for dentists to a digital workflow.

Evaluation of the hypothesis

To conduct this proof of concept, a plaster model (PM) obtained by duplication of a denture was photographed and five digital models (DM) were made. Therefore, since this study was not conducted on humans, it is in accordance with the guidelines for research ethics.

Image achievement

The PM was positioned on the center of a platform with approximately 40-cm height and lined with black fabric. An EOS Rebel T3i (Canon®, Japan) camera with Macro lens EF 100 mm (Canon®, Japan) stabilized on a tripod at about 45 cm from the model was used to capture the images. Autofocus or flash were not used, since they can lead to reconstruction deformities. The equipment configuration was standardized at ISO 100 and diaphragm aperture of 32. This setting was used to maintain a high clarity in all parts of the PM in all photographs, without blurring the extremities of the pictures (Fig. 1).

Each DM was generated from 50 photographs taken surrounding the PM in ambient light, and each group of photos was achieved on different consecutive days. The model was in a hermetically sealed container at these intervals.

The photographs were taken in three planes (Fig. 2):

- Parallel to PM occlusal plane: 24 photos, one every 15°;
- Angled at 45° in relation to PM occlusal plane: 24 photos, one at every 15°;

- Perpendicular to PM occlusal plane: 2 photos, with one focusing on each hemi-arch.

The 24 parallel and the 24 angled in 45° pictures were obtained in intercalated positions to achieve less repeated patterns and more distinct details.

Image processing and 3D reconstruction

The images were processed using 3DF Zephyr Free® software (3D Flow®, Italy). This software works semi-automatically, simply by uploading the photos and configuring the reconstruction process. For this protocol, all settings were maintained in high detail and for approximate objects. At first, the software pairs the inserted photos. From them, it creates a cloud of scattered points, identifying the three-dimensional position of common points in two or more photographs. From this, a dense cloud of dots is created, which finally generates the three-dimensional mesh of the object and its texture (Fig. 3). The process was conducted for each group of photographs to obtain the 5 DM (Fig. 4).

Measurement of models

To evaluate the reproducibility of the technique, the height (TH) and width (TW) of all teeth were measured in the DM, as well as the distance between the canine cusps (C–C) and the mesiobuccal cusp of the first molars (1 M – 1 M). Measurements were made using Blender® software (Blender Foundation®, The Netherlands). Since a measure of reference is necessary during photogrammetry, all DM were resized and the height of the maxillary right central incisor of the PM was used for calibration. TH and TW were also recorded on the PM with the use of a digital caliper. The values were obtained in millimeters, with accuracy of two decimal points.

Statistic

All data were recorded and saved in Microsoft Excel 2016® file (Microsoft®, United States). The difference between measurements of the PM and the mean of all DM was evaluated by ANOVA. The agreement between the measurement techniques was evaluated using the Bland-Altman method on the Analyze-it plugin (Analyze-it®, United States). The accuracy of the DM was evaluated by their superimposition using Geomagic® Control X™ software (3D Systems, USA) and the Analyze-it plugin (Analyze-it®, United States).



Fig. 1. Photographs taken with EOS Rebel T3i camera (Canon®, Japan) with EF 100 mm Macro lens (Canon®, Japan) with ISO100 and F32 configuration.

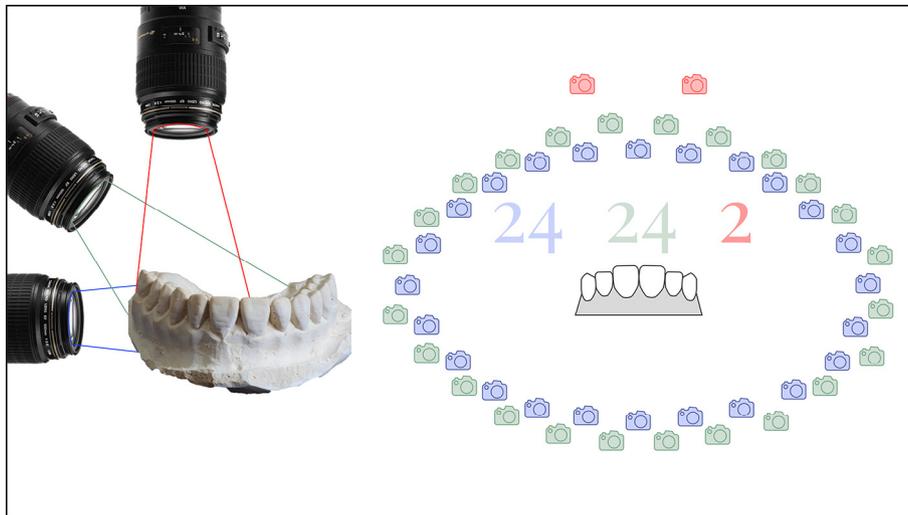


Fig. 2. Angle of incidence of the three planes photographed and positioning of the 50 photographs around the plaster model.

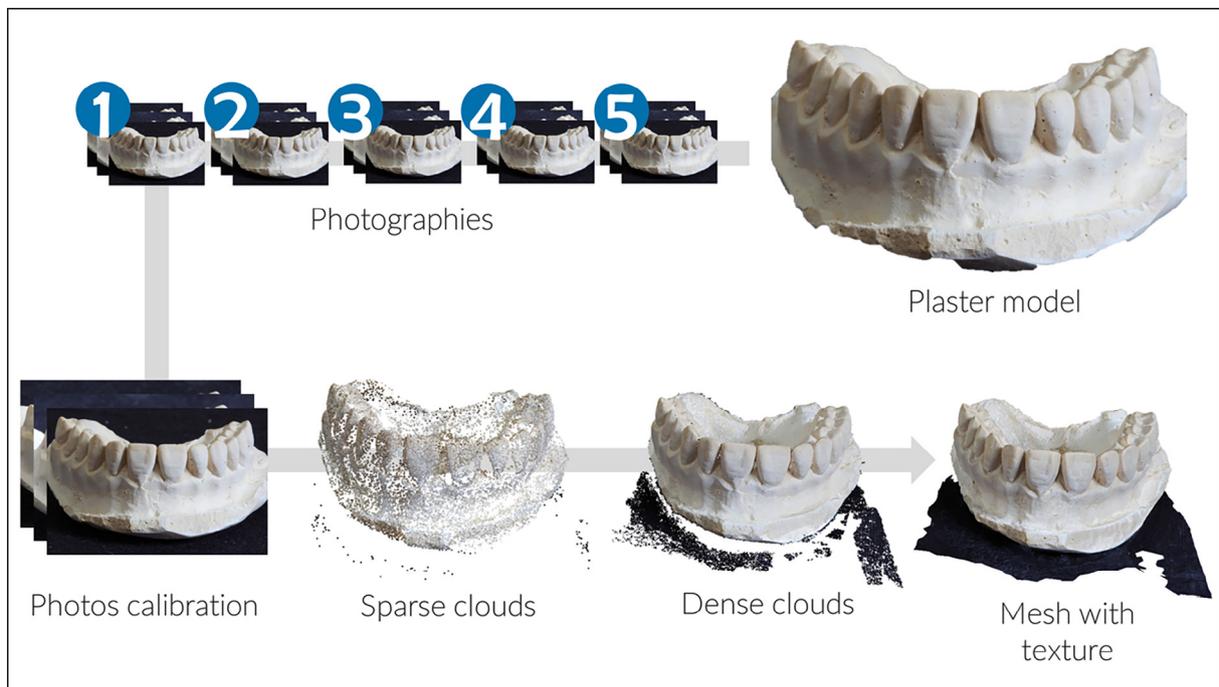


Fig. 3. Flowchart of the process of obtaining a digital model from the photogrammetry.

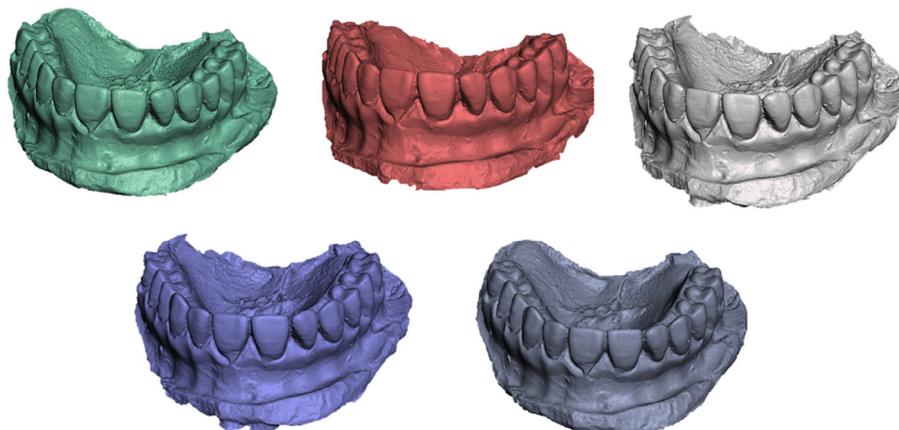


Fig. 4. The five digital models resulting from the reconstruction using five sets of distinct photographs. In the figure, the models are without texture.

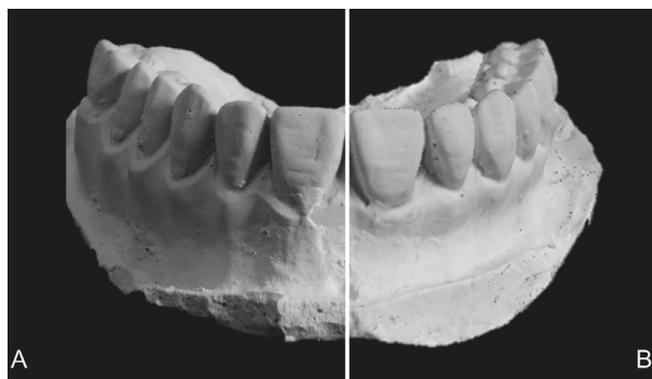


Fig. 5. Comparison of the physical plaster model (A) with the digital model with texture (B).

Table 1
Measurements obtained for the DM and PM.

Measures (mm)		PM	DM1	DM2	DM3	DM4	DM5
Upper right first molar	height	7.19	7.05	7.38	7.25	7.21	7.26
	width	8.91	8.76	8.98	8.79	8.73	8.87
Upper right second premolar	height	9.77	10.32	10.07	9.92	10.30	10.26
	width	5.85	6.03	6.02	6.08	5.82	5.98
Upper right first premolar	height	9.57	10.00	9.90	9.91	9.79	9.97
	width	5.78	6.14	6.09	5.95	6.00	5.94
Upper right canine	height	10.89	11.16	10.85	11.01	11.04	10.96
	width	7.44	7.30	7.19	7.52	7.21	7.29
Upper right lateral incisor	height	10.17	9.80	9.84	9.98	10.37	10.15
Upper right central incisor	width	6.55	6.32	6.24	6.51	6.43	6.27
	height	10.67	10.67	10.67	10.67	10.67	10.67
Upper left central incisor	width	8.01	7.90	8.10	8.17	7.90	8.29
	height	10.33	10.25	10.55	10.44	10.57	10.35
Upper left lateral incisor	width	8.09	7.98	8.19	8.12	7.92	7.97
	height	9.44	9.37	9.61	9.74	9.74	9.47
Upper left canine	width	6.41	6.29	6.21	6.34	6.30	6.42
	height	10.35	10.35	10.28	10.41	10.52	10.55
Upper left first premolar	width	7.07	7.09	7.03	7.26	6.95	7.38
	height	8.5	8.76	8.90	9.00	9.05	8.79
Upper left second premolar	width	5.6	5.54	5.81	6.00	5.68	5.79
	height	9	9.06	8.91	9.25	9.25	9.23
Upper left first molar	width	5.56	5.47	5.52	5.70	5.46	5.66
	height	6.28	6.50	6.63	6.52	6.28	6.54
C–C	width	9.09	8.85	8.65	8.93	8.94	8.95
1 M – 1 M	height	32.81	33.12	33.25	33.64	33.25	32.73
	width	51.06	51.25	51.78	52.52	51.82	52.19

No statistically significant difference between the values ($p > 0.05$, ANOVA). PM: Plaster Model; DM: Digital Model; C–C: distance between the cusps of the canines; 1 M – 1 M: distance between the mesiobuccal cusp of the first molars.

Pilot data

All models presented high quality (Fig. 5). The values found for PM and DM measurements are shown in Table 1.

The means and the limit of agreement obtained by the Bland-Altman analysis when comparing the measurements obtained on the PM and DM can be observed in Fig. 6. The measurements of height and thickness of teeth were defined between the limits of -0.4 to 0.6 mm, indicating good agreement between the measurement methods. When comparing the values of C–C and 1 M – 1 M, it was possible to notice a greater disagreement in the latter, suggesting lower precision in the DM arch as it progresses to the posterior region. The precision between the DM measurements showed a SD of ± 0.171 and a repeatability coefficient of 0.474 (Fig. 7). High SD values indicate a lack of agreement

between repeated measures. This was observed in the two isolated spots on the right side of the graph, corresponding to measurements C–C and 1 M – 1 M.

The accuracy values of superimpositions can be checked in Fig. 8 for full DM, and in Fig. 9 when only the right posterior segment of the DM was used. The delimitation of a smaller dimension favored the reduction of deformations, as shown in Fig. 10. Thus, when the models were fragmented, there was considerable reduction of the discrepancy values.

Discussion

The objective of this pilot study was to evaluate the use of photogrammetry as a viable technique for the digitization of plaster models, thus serving as an inclusive tool for dentists who do not have access to higher technology equipment. Since the focus of this study was accessibility, numerous protocols and software were tested to obtain a methodology that achieved the best results requiring the lowest financial investment. For this reason, free software was prioritized.

Usually the first contact of dentists with three-dimensional models occurs with reconstructions derived from Digital Imaging and Communications in Medicine (DICOM) files generated by computed tomography scanners. Although tools such as cone beam computed tomography (CBCT) have revolutionized dental practice by incorporating important information for diagnosis and treatment planning [21], its use in the three-dimensional reconstruction of intraoral tissues still has some limitations. The quality of reconstructions is affected by the presence of artifacts in the oral cavity, such as metallic restorations, by the patient's movement during examination and by the poor definition of the occlusal surfaces [22]. Thus, intraoral reconstructions obtained by CBCT data usually do not have great accuracy [22]. In addition, the acquisition of CBCT exposes the patient to considerable radiation doses [21], which is not justifiable only for scanning the dental arch.

An interesting approach for using CBCT to scan dental arches without the aforementioned limitations is to scan a traditional impressions, with some studies showing good accuracy in digital models obtained by this technique [23–25]. Although this is a viable alternative, this technique is sensitive to deformation of the impression material, thus CBCT should be performed as soon as possible after impression [23]. In addition, it requires the dentist to have access to a CBCT scanner and to have basic knowledge in digital modeling software.

The need for high initial investment or access to a service center is also limited in other digital scanning techniques. The evolution of intraoral and extraoral scanning has allowed rapid and accurate results [26], making it the most commonly used technique for this purpose currently. Initially, scanning in dentistry was initiated by indirect techniques of data acquisition by scanning plaster models; however, new technologies allowed *in-situ* dental scanning [27]. One of the advantages of intraoral scanning is the direct acquisition of information, eliminating the need for impression and achievement of a plaster model, thus reducing the possibility of accumulation of imperfections resulting from these processes.

In an *in vitro* study, Su et al. [28] found as a result of 3D standard deviation in intraoral scanning values up to $88.44 \mu\text{m}$ when testing various configurations of dental preparations, ranging from single crowns to crowns on all teeth in the arch. When extraoral scanning was used, this value decreased to $24.33 \mu\text{m}$. Since the largest discrepancies in intraoral scanning occurred when more than half of the arch was involved, the authors contraindicated this type of scanning for larger scales [28]. On the other hand, for the scanning of more restricted sites, the intraoral scanner seems to be the most appropriate. Güth et al. [29] scanned a titanium model representing a preparation of a molar and a premolar in an *in vitro* study. As a result, they obtained a 3D standard deviation of $19 \mu\text{m}$ for the intraoral scanning, $31 \mu\text{m}$ for oral scanning of

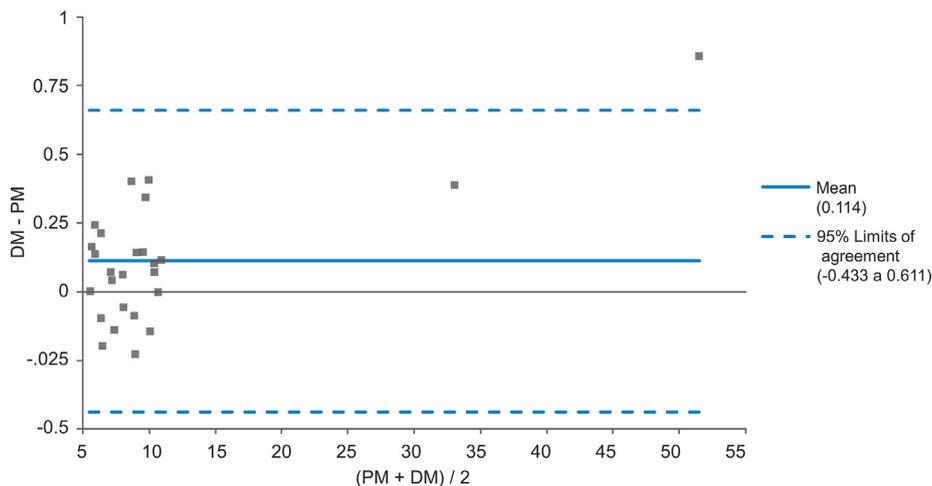


Fig. 6. Bland-Altman plot comparing the values obtained with the measurements in millimeters for PM and DM.

the impression and 52 μm for the extraoral scanning of the plaster model. The same was observed by Sason et al. [30], who scanned mandibular molars in vivo and observed an accuracy between 20.7 and 33.35 μm in the intraoral scan and 19.5 to 37 μm in the extraoral scan. However, it is worth mentioning that the results depend not only on the scanning method, but also on the system used [26].

For many years, photogrammetry has depended on the use of special equipment for image acquisition and processing [31], making it difficult to apply. However, in recent years advances in the field of digital photography and the creation of specific software have made this application financially accessible, reliable and accurate, becoming an interesting resource for dentistry [9,10,18,32,33]. The technique has already been employed by Ravasini et al. [18] to quantify the dental material removed from wax dentures after grinding, concluding that photogrammetry is a method of high versatility, good accuracy and low cost. Rivara et al. [9] took advantage of the three-dimensional coordinates obtained with photogrammetry to evaluate the discrepancy between the clinical position and the digital planned position of dental implants, concluding that this is a reproducible and viable technique.

Bergin et al. [32] also considered photogrammetry as a technique to obtain the three-dimensional position of total arch implants, achieving more accurate results than with traditional impression. Bratos et al. [33] evaluated the accuracy of photogrammetry for full-arch recording, concluding that this is a viable technique without statistically significant difference compared to conventional implant impressions ($p > 0.05$). In addition, the results obtained were in the range of the machining tolerance of implant components and within the CAD/CAM milling procedures capacities, thus being suitable for these applications.

In a case report, Sánchez-Monescillo et al. [10] performed a direct clinical application of photogrammetry for a full-arch immediate

rehabilitation. Seven implants were placed in the patient's mandible and their positions were recorded using a photogrammetric technique. This process generated an STL file, which in turn was combined with another STL file containing the patient's pre-extraction teeth obtained from extraoral scan of the model, and another STL file containing the soft tissue obtained by scanning the model obtained after extraction. The superimposition of these elements allowed placement of the restoration seven hours after surgery. Clinical and radiographic results indicated good condition of the peri-implant tissue after 1 year, without screw loosening or other mechanical or biological complications.

Although it has already been used by several studies, the authors of this pilot study are unaware of a more simplified and accessible protocol than the one proposed here. Since the conception of this study, the authors never expected a superiority of the proposed methodology against intraoral or extraoral scans. The priority of the established protocol was to create a practical and simple methodology to dentists though at the cost of a certain quality that might be achieved with more complex and expensive protocols. Thus, as expected, our results were inferior than those obtained with traditional dental scanning techniques.

A previous measure that could contribute for better results is the calibration of lenses. Optical aberrations resulting from lens design and production are common on all cameras, leading to distortions in the equipment sensor [34]. These distortions are expected on all lenses because of their material, shape, lens configuration to achieve varying focal lengths and other photographic parameters. This can lead to image change in the pixel matrix, altering the geometry, position and size of the represented pixel and resulting in distortion of the final image [34]. In addition, other parameters could be considered to optimize the results obtained with photogrammetry, like increasing the

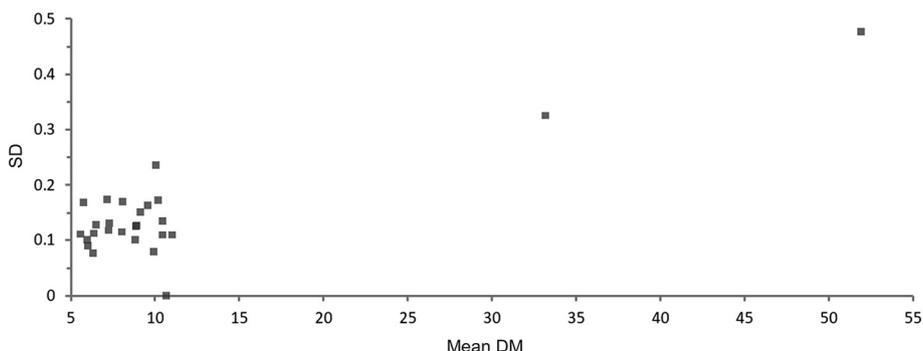


Fig. 7. Evaluation of the accuracy of DM measurements.

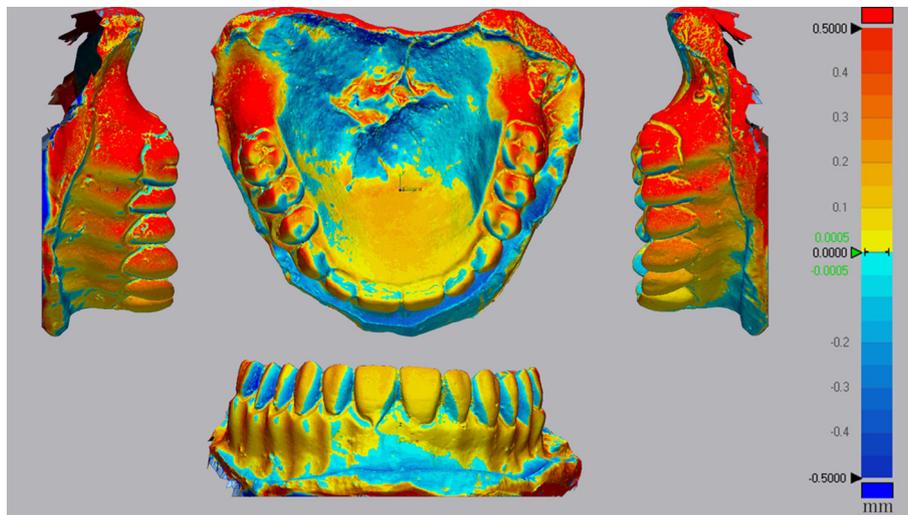


Fig. 8. Superimposition of 5 DM with discrepancy ranging from -0.5 mm to 0.5 mm. Dark colors indicate higher values, being positive values for hot colors and negative for cold colors. The greatest areas of discrepancy were the region of the posterior teeth and the posterior third of the palate.

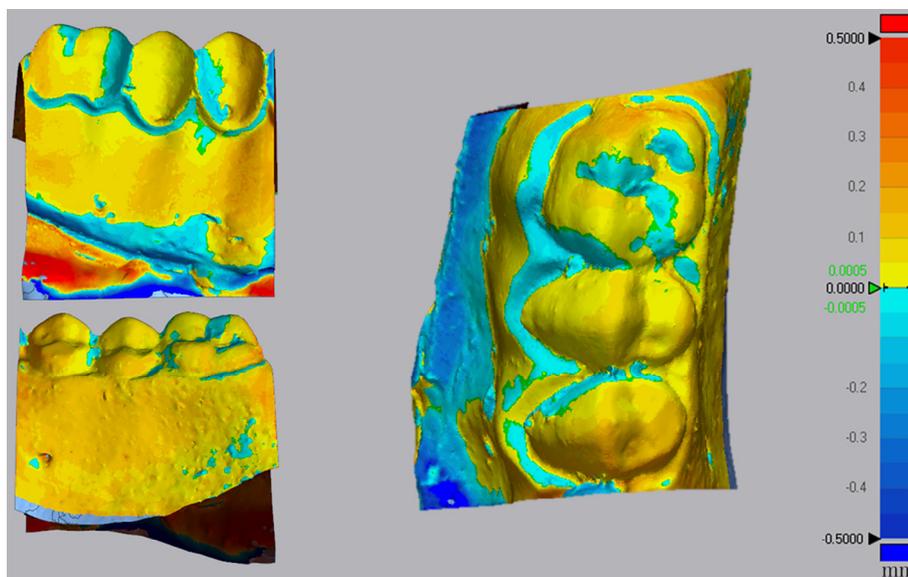


Fig. 9. Superimposition of the segments of the right posterior segment of the DM with discrepancy ranging from -0.5 mm to 0.5 mm. Dark colors indicate higher values, being positive values for hot colors and negative for cold colors. The value of the discrepancy was considerably reduced with this approach.

maximum angle and the number between homologous rays, using manual collimation and increasing the distance between object and camera [18]. Another measure that could contribute to improve the results is the incorporation of target references to serve as guides for image processing by the software [33]. None of these processes was included in our methodology because the authors considered that these extra steps could limit the use of the technique to only a few dentists, and our greatest care was to make the technique reproducible for the majority.

Regarding the analysis of results, the technique of image superimposition may also have influenced the study outcome. The superimposition of models was based on a “best fit alignment” algorithm used in other studies of this type [28], but is still not free of flaws.

Since this is a pilot study, it is unwise to extrapolate our results for immediate clinical application. From a prosthetic point of view, our results fall short of what is required for a favorable adaptation to periodontal and peri-implant tissues [35,36]. From a surgical perspective, the use of the technique seems more feasible, since in surgical procedures a millimeter scale is sufficient to protect anatomical structures

[37]. Still, its use depends on more evaluations, and the use of smaller areas, such as guides for single implants, seems more indicated than in complete arches.

Another application worth addressing is the use of photogrammetry for the archiving of digital models for legal purposes, dispensing the need for large spaces to store physical models and facilitate the clinical organization.

While this technology still does not provide enough precision or proven accuracy for incorporation into the treatment flow, it is an interesting tool for the diagnosis, planning, and archiving of documentation. More studies are needed before this methodology can be indicated for a clinical application, such as for the preparation of guides for guided implant surgery. Future protocols should be tested with the adoption of new tools, such as the incorporation of target references, other photographic settings and alternative software.

Declaration of Competing Interest

The authors do not have any conflict of interest.

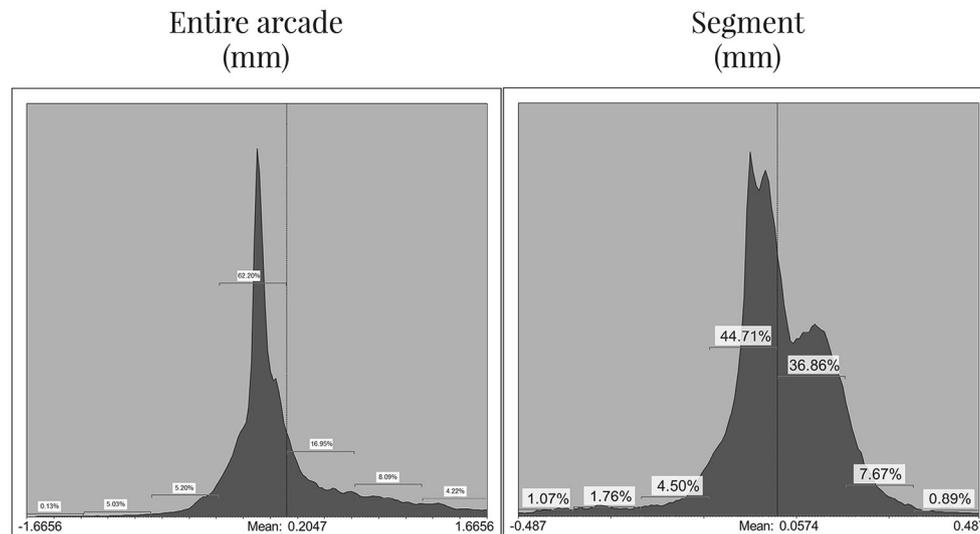


Fig. 10. Distribution of the adaptation between DM when the entire arcade is used (left) or only the right posterior segment (right).

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