



Three-dimensional Comparison of Two Types of Indirect Digitization with Inverse Engineering Technique

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Abstract

Aim: To evaluate the accuracy of extraoral digitization using an inverse engineering technique comparing indirect scanning of conventional silicone impressions and resulting gypsum models.

Materials and Methods: Thirty polyvinyl siloxane impressions from a master cast of a left first maxillary molar preparation were scanned and 30 STL files were obtained. The 30 resulting gypsum models were scanned and both groups were aligned with the reference STL file of the master cast using a computer-aided 3D technique (best fit algorithm). The exact distances (mm) at the level of the finishing line on the buccal and palatal sides of both groups were measured and compared to the reference group. A repeated measures analysis of variance was performed with two intraindividual factors.

Result: Based on the average values of absolute deviations between the test and reference datasets, it was demonstrated that the silicone group produced more accurate results ($20 \pm 20 \mu\text{m}$) than the plaster group ($80 \pm 80 \mu\text{m}$). The results were significantly better in the silicone group ($p < 0.01$). There were no differences between the buccal and palatal sides ($p = 0.23$) with no significant interaction between the two factors ($p = 0.141$).

Conclusion: The digitization of silicone impressions was significantly more accurate than that of plaster casts. However further studies are necessary for all relevant variables.

Clinical Significance: The benefits of CAD/CAM technology in the prognosis of fixed prostheses necessitates evaluation of all existing varieties of digitalization, with indirect scanning being a way to achieve it with least economic investment for the dentist.

Keywords

CAD/CAM; Three-dimensional measurements; Computer-aided analysis; Scanning silicone impressions; Scanning stone replicas; STL

Introduction

The choice of impression technique influences the precision of dental impressions, and therefore the fit of the resulting restoration [1]. There are several factors that influence the end result of conventional impressions, such as their potential distortion due to limited storage capacity, their disinfection in antiseptic solution, their partial or total separation from the impression tray, and alterations in climatic conditions during the process that can result in dimensional changes [2-4].

Advances in computer-aided design (CAD) and computer-aided manufacturing (CAM) technology have eliminated most of the factors that negatively affect conventional impressions, allowing the dental anatomy to be reproduced perfectly. With the CAD software, functional occlusal morphologies that are equal or superior to those manually designed by laboratory technicians can be achieved [5].

In 1985, French software engineer Dr. Alain Ferru created the two-dimensional CEREC1 operating system with which inlays could be made [6], and pioneers such as Mörmann, Duret, and Rekow imagined a plethora of possibilities of CAD/CAM technology in dentistry [7]. Since then, CAD/CAM technology has undergone notable changes.

Although the digital impressions seemed to be superior to conventional impressions, there was some controversy. Since the introduction of the CEREC system, many commercial

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intraoral and extraoral scanners have been developed, each with more accessible systems to facilitate access by dental offices.

There are studies that compared the internal and marginal fit of the crowns manufactured by the digital and conventional impression methods and found that they had similar marginal adjustments [8,9].

Other studies compared the accuracy of intraoral full-arch digitization (direct digitization) with the digitized gypsum models obtained from poured alginate impressions (indirect digitization). No significant differences were observed between the groups of digital models and most patients preferred the alginate impressions because they were easier and faster, although less comfortable. Despite the high precision of intraoral scanners, it was concluded that alginate impressions were preferred [10].

Therefore, there is still a great discussion among authors about the efficiency of obtaining impressions with conventional methods, direct digitization or indirect digitization. One of the reasons for the insufficiency of some conventional impressions is the difficult visibility of the subgingival margins of dental preparations, which is directly related to the inadequate handling of soft tissues at the time of impression. However, the digital impressions alone will not solve this problem [11].

Flügge et al. [12] compared the precision of intraoral scanning (iTero) with extraoral scanning (iTero and D250 3Shape), based on the deviations between the STL models obtained in each group. The best results were obtained for extraoral scanning with the D250 3Shape, and the intraoral scanning with iTero was less accurate than extraoral scanning with iTero, probably because of the adverse effects of intraoral conditions [12].

On the other hand, due to the high cost involved in this technology in a dental practice, there are many professionals who take conventional impressions and it is in the laboratory where the extraoral scanning is performed, either by scanning the silicone impression or the gypsum model, to later perform a CAD / CAM rehabilitation. Currently few studies have evaluated and compared these two types of extraoral digitization. Therefore, it is necessary to know the accuracy of this type of digitization for it to become a common practice in prosthetic dentistry.

The aim of this in vitro study was to verify if there existed significant differences between two extraoral digitization (indirect digitization) techniques obtaining the STL datasets.

The null hypothesis was that no significant difference would be found between these two methods.

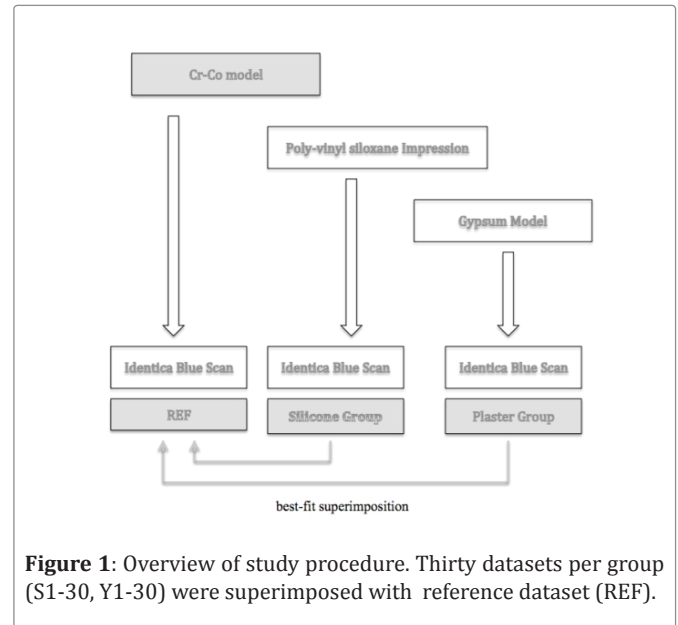
Materials and Methods

A reference cobalt-chromium (Co-Cr) alloy model of the first left maxillary molar was fabricated using CAD/CAM. This represented a preparation for a complete crown with a chamfer finish line. We then compared the accuracy of three-dimensional data sets acquired indirectly from either digitized silicone impressions (the silicone group) and digitized gypsum models (the plaster group). Digitization of surface reference data was done with a laboratory scanner (Identica Blue®, Medit) in all cases. The STL data set for the reference Co-Cr alloy model was defined as the reference data (REF). The same scanner was used to perform all digitization. Figure 1 demonstrates the study procedure in detail.

Data Capture by indirect digitization

Thirty polyvinyl siloxane impressions of the master die were made with low-viscosity (Turboflex®, R & S, Light Normal Set) and high-viscosity (Turboflex®, R & S, Putty Soft Normal Set) materials. These materials were compliant with ISO 4823. Small-perforated plastic cups, measuring 30 mm in diameter and 20 mm in height were used as impression trays and the master die was adjusted to be placed centrally in the middle of the cup.

The manufacturer's instructions were followed for the setting



time of the impression material, and the master die was then removed from the impression. For each impression, the two components of high-viscosity polyvinyl siloxane material (base and catalyzer) were mixed, always in the same quantity (half of the measuring spoons) and placed in the container. Then, the low-viscosity polyvinyl siloxane material was applied to the tip of the syringe over the metal die, and after 5 s, the container full of high-viscosity silicone was placed on the covered die of low-viscosity silicone. After 5 min, according to the manufacturer's instructions, the container was removed from the die and excess material was cut with a scalpel and sterile sheet (Aesculap Division®, B. BRAUN), complying with ISO 11607. Each of the silicone impressions was numbered with a permanent marker in the order of production (1–30).

To facilitate spatial recognition of the impression during scanning, the buccal, palatal, distal, and mesial aspects were marked with a V, P, D, and M, respectively. The Helling 3D Scan Spray (Helling GmbH), which complies with ISO 9001, was used to facilitate scanning of the 30 silicone impressions. Spraying the impressions achieved a minimum uniform covering of easily removable fine-grain titanium dioxide (TiO₂) particles (average size, 2.8 µm). Within 6 h, all 30 impressions were sent to a laboratory and scanned with the Identica Blue® device.

Immediately after creating the silicone impressions, type IV stone (Hebohard, Hebo® Spain SA) (ISO 6873) was mixed according to the manufacturer's instructions and poured into the impressions. Type IV stone is recommended when strength and hardness are required with low setting expansion. According to the manufacturer's information, the expansion was 0.25%, the compression resistance was 60 N/mm², and the setting time was 12–15 minutes. The 30 plaster models obtained from each of the silicone impressions were scanned using the Identica Blue® device within the first 48 h of pouring.

The images obtained from scans were saved in STL format (Surface Tessellation Language) for CAD/CAM data exchange, and were numbered from S1 to S30 for the silicone group and from Y1 to Y30 for the plaster group. Finally, all the STL files of both groups were exported to the Geomagic software (Studio 11® Geomagic) for later analysis.

Alignment of data sets

All STL datasets were imported into the Geomagic® inverse engineering software (Studio 11®, Geomagic, Morrisville, NC, USA). Each of the 30 datasets of the Gypsum (Y) and the silicone group (S) were aligned with the reference data set (REF) using a best-fit algorithm. With this technique, all STL files were overlapped, matching all possible orientations and selecting the one with the

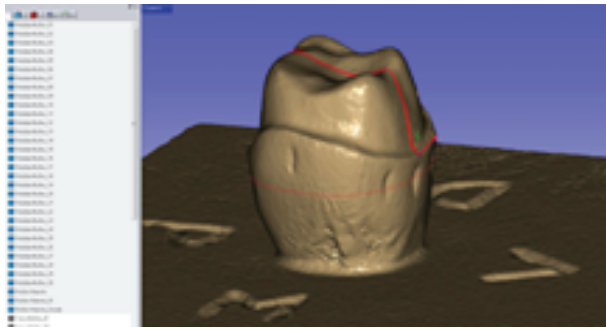


Figure 2: Superposition of the total STL files with best fit algorithm. Full set comprises silicone + plaster + reference groups.

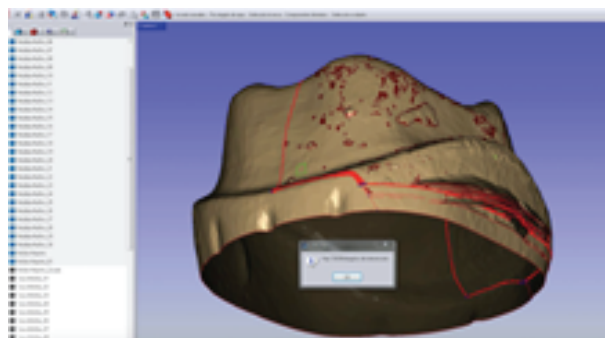


Figure 3: Selection of area of interest of STL file set. Full set comprises silicone + plaster + reference groups.

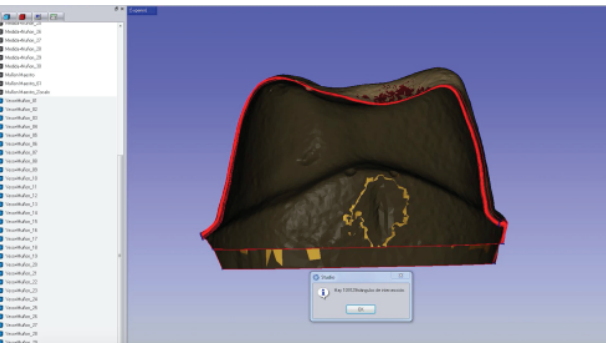


Figure 4: Sagittal section from vestibular to palatal surface in full set of STL data. Full set comprises silicone + reference and plaster + reference data. Images are superimposed from buccal to palatal side.

best object-to-object penetration [13] (Figure 2). In this case the application was used to find three points of anatomical similarity (three cusps) so that the software could recognize in all the files leaving the set of STL of each group (S) and (Y) completely aligned with the reference STL (REF).

To ensure accurate overlap, the data sets were reduced to the field of interest by removing all artifacts and irrelevant areas below the preparation line (Figure 3).

3D Analysis of divergence

Once the data sets were superimposed, a central area was selected on the free sides (vestibular and palatal) at the level of the finishing line of the molar preparation as the interproximal sides between the adjacent teeth are normally hidden in the dental arch.

Then, using the Geomagic® software, we made a sagittal section

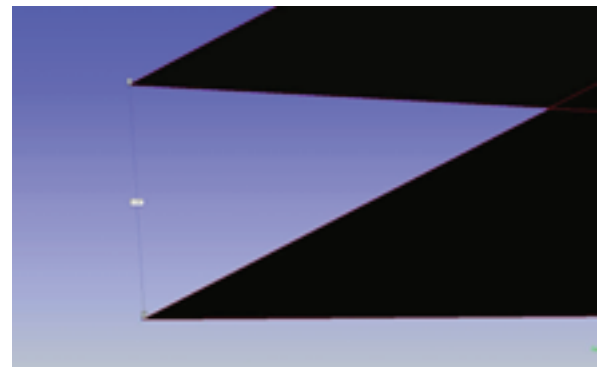


Figure 5: Detail of measurement (mm) between STL S1 of silicone group and reference STL.

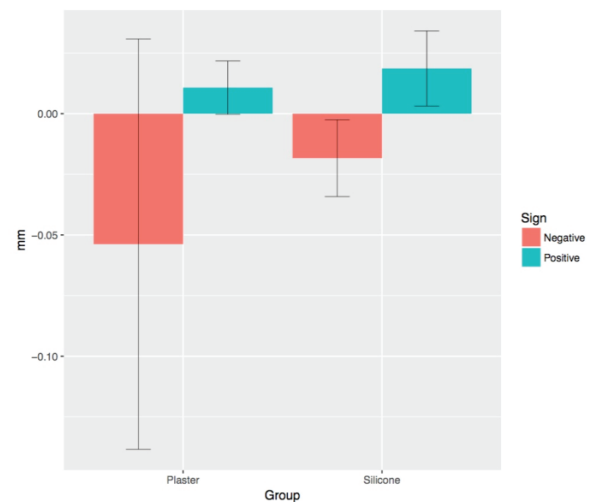


Figure 6: Mean positive and negative deviations (mm) and standard deviation after superimposition of reference dataset with 30 datasets received from each group.

from the vestibular side to the palatal side in the whole set of superimposed STL data (silicone + REF, plaster + REF) to identify exactly the same area of study in each group. This ensured that the same measurement parameters were used (Figure 4). Subsequently, the STL data of each group were matched with the REF STL and measurements were compared. The Euclidean distances (in mm) were obtained for each measurement point on the vestibular and palatal sides between each pair of silicone STL (1–30) + REF STL and each pair of Plaster STL (1–30) + REF STL data. All discrepancies between the group STL and the REF STL values were measured in millimeters and expressed as positive and negative mean deviations (Figure 5). For each alignment, the mean and standard deviation of the absolute values of the Euclidean distances were calculated. Statistical software R version 3.4.1 (2017) was used for the statistical analysis.

Statistical analysis

A repeated-measures analysis of variance was performed with two intraindividual factors. Each silicone impression was paired with a plaster model, to allow us to consider the technique (Group factor: Silicone or Plaster) as a repeated factor at two levels. The other factor taken into consideration was the side (Vestibular or Palatal) of the teeth. Thus, the group factors were silicone versus plaster, and the side factors were buccal versus palatal. Because the data were not normal, even after logarithmic transformation, the p-values were obtained using permutation tests for the repeated-measures lineal model ($\alpha = .05$). Analysis was carried out with the “EZ” package of the R software (version 3.4.1, 2017).

Positive values							Negative values				
Group	Side	n	Mean	Median	Sd	IQR	n	Mean	Median	Sd	IQR
Plaster	Palatal	0					29	-0.04	-0.03	0.04	0.04
	Vestibular	4	0.01	0.01	0.01	0.01	26	-0.07	-0.04	0.12	0.03
	Global	4	0.01	0.01	0.01	0.01	55	-0.05	-0.04	0.08	0.04
Silicone	Palatal	7	0.02	0	0.02	0.02	21	-0.02	-0.01	0.02	0.03
	Vestibular	18	0.02	0.02	0.01	0.02	12	-0.01	-0.01	0.01	0.01
	Global	25	0.02	0.02	0.02	0.02	33	-0.02	-0.01	0.02	0.02

Table 1: Descriptive statistics of discrepancy for positive and negative values (mm), with zero values discarded

Group	Side	Mean	Median	Sd	bootstrap 95% CI mean	IQR
Plaster	Palatal	0.04	0.03	0.04	(0.03,0.06)	(0.01,0.05)
	Vestibular	0.06	0.04	0.11	(0.04,0.14)	(0.02,0.06)
	Global	0.05	0.03	0.08	(0.04,0.09)	(0.01,0.05)
Silicone	Palatal	0.02	0.01	0.02	(0.01,0.03)	(0,0.03)
	Vestibular	0.02	0.02	0.01	(0.01,0.02)	(0.01,0.02)
	Global	0.02	0.01	0.02	(0.01,0.02)	(0.01,0.03)

Table 2: Descriptive statistics of discrepancy in absolute values (mm)

Effect		p p<.05
1	Group	0.00*
2	Side	0.23
3	Group:Side	0.14

Table 3: Analysis of variance permutation analysis. Results of silicone group were better than those of plaster group ($p < 0.01$), but there were no differences between the sides ($p = 0.23$) and there was no significant interaction between factors ($p = 0.141$).

Results

Figure 6 illustrates the positive and negative deviations of the average Euclidean distance values for both groups.

Table 1 lists the divergences after overlap of the sets of STL data for each digitized impression in each group, individually compared with the control REF group. Regarding positive deviations, the silicone group showed higher divergences ($20 \pm 20 \mu\text{m}$) compared to the plaster group ($10 \pm 10 \mu\text{m}$). Regarding the negative values, the plaster group showed higher divergences (-50 ± 80) than the silicone group ($-20 \pm 20 \mu\text{m}$).

Figure 7 provides the mean absolute values of Euclidean distances for both groups compared to the REF STL.

Table 2 summarizes the measurements of the average space (mm) in absolute values by scanning technique (plaster/silicone) and location (vestibular/palatal) compared to the REF STL. The interquartile ranges (25th to 75th percentiles) of the average space measurements for each technique were 0.01–0.05 for the plaster group and 0.0–0.03 for the silicone group. Using absolute values, smaller discrepancies were observed in the silicone group ($20 \pm 20 \mu\text{m}$) than in the plaster group ($50 \pm 80 \mu\text{m}$) when compared to the REF STL.

In Figure 8, the vertical bar represents the minimum significant difference by Fisher's test ($P = 0.023$). From the results of the permutation test in Table 3, we concluded that there are differences between groups ($p < 0.01$), the silicone group being better than the plaster group; and there were no differences between the vestibular and palatal sides ($p = 0.23$) and there was no significant interaction between the two factors ($p = 0.141$).

Discussion

The null hypothesis that no difference would be found in the STL data set by using two types of extraoral digitization was rejected. According to the results of this study, considering the absolute values, the silicone group was better, with smaller divergences from the plaster group when compared to the reference group. Three-

dimensional data can be evaluated in many ways. In one of these, Schaefer et al. [14] reported that three-dimensional analysis of in vitro data was possible by superpositioning STL files and evaluating the adjustment of mechanized inlays of lithium disilicate when scanning with different intraoral scanners. The STL files obtained from scanning these dental preparations were then superimposed on the STL files corresponding to the virtual design of the inlays, using a best-fit method. It was concluded that there were significant differences between some scanners, but the marginal discrepancies were within acceptable limits. Some discrepancies with negative values were found in alignment at the level of the finishing line, indicating areas that need to be adjusted before the final cementing. A similar difficulty was found in the present study. As with this and other published studies [14–19], STL data were evaluated by comparing and referencing data using a best fit method.

Although previous studies have compared three-dimensional STL data sets [15,20–23], this is the first study in which axial cuts were made to measure the exact distance between the reference and test data. Despite its precision, positive and negative deviations occurred between the reference and the test data. Güth et al.[12] reported that calculating the arithmetic mean of these deviations is known to produce results close to zero and did not show adequate real divergence [15]. Using the positive and negative deviations and the standard deviation to estimate the proximity of each set of test data in relation to the reference, they calculated the average of the absolute Euclidean deviation for each group. This value gave the average distance between each set of test and reference data, without considering whether it was located "above" or "below" the reference surface. A similar analysis was used in the present study, but instead of taking data sets, the exact distance between test data for each group was compared to that of the reference data. It has been shown that a variation is possible during the process of overlaying STL files that can affect the measurement results [24]. As in other studies [1,2,11], in this study the greatest margin of error was found in the plaster group and could be explained by numerous laboratory procedures, although contraction of the impression material is thought to be compensated for by the expansion of the gypsum model [15]. In other research, Shembesh et al. [25] compared the marginal adaptation of

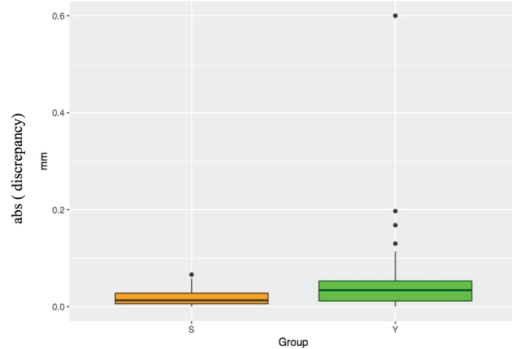


Figure 7: Box plot showing absolute Euclidean distances (mm) of both silicone and plaster groups compared with reference dataset (REF).

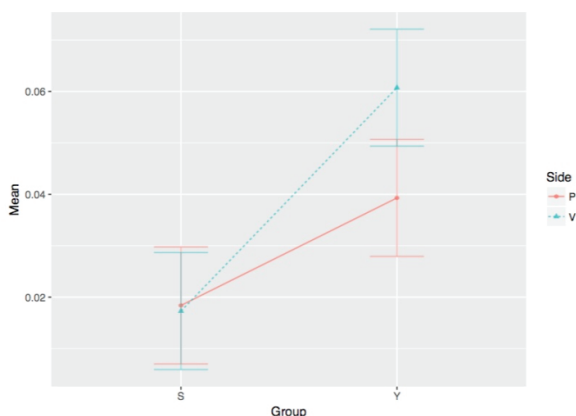


Figure 8: Diagram showing differences between silicone and plaster groups. Vertical bar represents the minimum significant difference of Fisher (0.023) and horizontal bar represents absolute values of silicone and plaster groups (red line: Palatal side, green line: Buccal side).

three-unit fixed zirconium prostheses in vitro and found that the best results resulted from intraoral scans with the Lava True, followed by scans of plaster casts, third intraoral scans with the Cadent iTero, and lastly, scans of silicone impressions. However, it should be noted that different zirconium oxide compositions and fixation cements also affect the quality and accuracy of the final restorations [25]. Therefore, many factors can influence outcomes.

Another factor that could affect the accuracy of digital substructures is the technology used by each device to capture the data. For example, iTero uses parallel confocal images in a point-and-click system, whereas Lava uses continuous active wavefront sampling in a video system. The accuracy of data acquisition and of the algorithms used in each system can affect the overall accuracy of the resulting digital impression. In addition, errors may occur during the image registration process and superpositioning of the images, which may cause an additive error effect [9].

Quaas et al. [19] evaluated the three-dimensional precision of the tactile digitization of ceramic models and silicone impressions of a maxillary canine and a mandibular molar, and concluded that the digitization was less accurate in silicone impressions due to the flexibility of polyvinylsiloxane during tactile scanning. Therefore, tactile digitization of impressions is not recommended because the probe has difficulties accessing zones like the finish line; however, this is less of an issue when performed with extraoral models. When assessing three-dimensional precision by superpositioning STL

files, the form of the tooth significantly affected the mean negative deviations and large negative deviations were observed in the areas of the finish line, as in the present study.

Persson et al. [18] compared the reproducibility of tactile digitization of master models of incisors, canines, premolars, and molars by digitizing gypsum models made from silicone impressions. It aimed to evaluate the dimensional changes in models after taking impressions and after pouring. Using best fit alignment in computer software, the tactile digitization of the master models was compared to that of the gypsum models, and it was determined that the form of the dental preparation affected the total number of point cloud with most obtained in canines, followed by premolars, incisors, and molars in descending order. It was also found that the number of points was higher in the upper occlusal portion, followed by the middle portion, with the fewest points in the cervical region. As in the present study, the plaster models tended to be larger in the cervical part compared to the reference model, obtaining negative values when performing the best fit.

Schaefer et al. [17] reported the effects of one-step or two-step impression methods, comparing the adjustment of five lithium disilicate inlays after scanning the restorations obtained through each method and comparing them with the scans of dental preparations. Single-step impressions were considered preferable to two-step impressions, especially when fabricating partial restorations.

Jeon et al. [26] evaluated the repeatability of digitizing canines, premolars, and molars for prosthetic pillars in conventional impressions with white light and blue light scanners. It was concluded that the better digitization was obtained with the blue light scanner.

Cho et al. [27] compared the accuracy and reproducibility of direct and indirect digital impressions by scanning gypsum models. The STL files were superposed with the best-fit technique and no significant differences were found between STL files obtained by intraoral scanning or scanning of the gypsum models, neither in the internal nor in the finish line. In both groups, negative values were found on the buccal side, meaning that they may require adjustment before cementing, and positive values were obtained on the palatal and interproximal (mesial and distal) sides, which could produce loosening of the cemented restorations in the future.

By contrast, we found that the plaster group had more negative values than the silicone group, and that both groups had higher negative values on the buccal side than on the palatal side. Generally, the differences in the results among authors are attributed to the materials used and the impression methods [27].

Chochlidakis et al. [28] conducted a systematic review of the marginal and internal fits of fixed restorations manufactured with digital and conventional techniques, to determine the effect of different variables on the accuracy of adjustment. The results showed similar discrepancies in both groups but those that came from digital techniques provided a better internal and marginal adjustment compared to the conventional techniques. Both the internal and the marginal discrepancies were greater when gypsum molds were digitized than when master models were digitized directly. Indeed, the greatest discrepancies were associated with the material of the master model (more with stereolithography or polyurethane dies and less discrepancy in digital dies) and with the restoration material (more with glass ceramic restorations compared to zirconia and metal alloy restorations). However, the manufacturing technique, restoration type and the conventional impression material had no effect [28].

Currently there is a great controversy about the best method of digital impression, but recent studies confirm that the marginal fit from CAD/CAM crowns made from scans of plaster models with laboratory scanners are comparable, and sometimes superior, to those obtained with other intraoral digital scanners [29,30].

Tsirogiannis et al. [31] performed a meta-analysis of all in-vitro and in-vivo studies of unitary restorations published to 2016. It was concluded that there were no significant differences when comparing the marginal discrepancies of the unitary ceramic restorations manufactured from digital or conventional impressions. Both the

digital and the conventional methods provide clinically acceptable fabrications of single-unit ceramic restorations [31].

However, it should be noted that a meta-analysis cannot be extrapolated or generalized without understanding the degree of heterogeneity (I^2) among the studies [32]. We therefore advocate calculating I^2 statistics for each study, with values of 25%, 50%, and 75% used to indicate low, moderate, and high heterogeneity, respectively.

This is an experimental in-vitro study, which could be part of a more exhaustive study that takes into account the different anatomies of the different teeth that will be part of a complete arch. In this study we have shown the divergences that exist in the digital impression of a molar, since it is the tooth that is mostly restored with a crown of monolithic material, but it would be interesting to extend this line of research.

Conclusion

In this study, the null hypothesis that no difference can be found between two types of extraoral digitization was rejected. Within the limitations of the in-vitro study, it was concluded that the scanning accuracy was superior in the silicone group than in the plaster group when compared to a reference model. Using the latest inverse engineering techniques, very good results were obtained in terms of accuracy in both groups; however, when considering the absolute values, the silicone group showed smaller divergences than the plaster group when compared to the reference group. There were no significant differences between the buccal and palatal sides.

The need to compare the results of both groups (gypsum and silicone) with the data obtained by intraoral scanning and the fact of having impregnated the silicone impressions with TiO_2 antireflective spray but not the gypsum models means that this study has some limitations.

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