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Analysis of the mesh resolution of an .STL exported from an intraoral scanner file

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Abstract

Objectives: This study aimed to provide information on the accuracy of exported digital files with the different resolutions available in the CEREC 4.6.2 software obtained by means of an intraoral scanner (IOS), in addition to establishing differences between materialized models with different exported resolutions, and how these different exported files can influence finite element analysis (FEA) simulations.

Materials and Methods: The upper complete arch of 10 patients was scanned through an IOS (CEREC Omnicam 1.0/Dentsply Sirona). Files of three resolution meshes digitalized by a CAD software (Cerec SW, 4.6.2) high, medium and low (IOSH, IOSM, and IOSL) were exported. Each file was evaluated by a software (NETFABB) about the number of triangles obtained and compared with the number announced by the manufacturer. Also, with a superimposition with a specialized software (GEOMAGIC X), the digital models were compared. The files of each resolution were printed (Sprintray 3D Printer), and the printed models were scanned with IOS (Omnicam 1.0) and compared with the control group (intraoral scanned high-resolution file, IOSH).

FEA simulations were imported into COMSOL and analyzed under different loading conditions.

Results: The number of exported triangles coincided with that reported by the manufacturer. The digital models from files of different resolution did not show significant differences (less than 1.5 um) between each other. Models printed (H, M, L) from files of the same resolution mesh (H, M, L) did not show significant differences between them either in partial measures of the arch and neither in the complete arch. FEA showed significant differences in stress concentration between different exported models.

Clinical Significance: Digital models can be exported and printed in three resolutions of the mesh, without differences clinically significative. On the other hand, for future FEA applications further research should be performed in order to determine the optimal number of triangles.

KEYWORDS
CAD/CAM, dental materials, digital dentistry

1 | INTRODUCTION

Digital systems in dentistry have changed several conventional processes of diagnosis, materials, planning, and treatment execution. The main purpose of having digital systems for the acquisition, design and manufacture of dental restorations is to obtain an exact result, be a user-friendly system, perform predictable lab and clinical procedures, diminish clinical times, make a more comfortable experience for the patient, standardize the processes, and improve clinical efficiency.[1,2]

The main objective of a scan (intra or extraoral) is to precisely obtain the three-dimensional geometry of an object.[3] Intra oral scanners (IOS) are devices that have been consistently incorporated into these workflows in contemporary dentistry.[4] Obtaining digital models from image acquisition with an IOS is another increasingly used process. To obtain accurate digital models, several factors influence, such as the scanner used, the scanning strategy, the scanning software, the quality of the exported meshes, the machining system, the material to print and the post-production of the model obtained.[1,4–6] Similar to what happens with the different types of conventional dental models, 3D printing can have various applications and differences between the final results.[1,5]

The quality of a digital impression is measured through resolution, defined as the sharpness of the image obtained from data acquisition.[7] Regardless of the scanner image capture method, the process leads to the three-dimensional capture of a cloud or pattern of points representative of the object and referenced spatially.[5] This point cloud allows the generation of a digital mesh, which is transformed into a 3D model due to the union of polygonal planes.[7,8]

These polygonal planes or triangulations form this digital mesh with common angles sharing the same edges, therefore establishing these standard triangle tessellations or stereolitography files (.stl), which are compatible with many applications.[9] The digital .stl file format is widely used in digital dentistry and its principle lies in the incidence of a light beam on an object. Through the acquisition unit, a point dependent on the distance where the light falls on the surface is located.[10] To effectively assess the quality of the digital meshes obtained, the accuracy of an IOS must be considered.[11–13] According to the ISO 5725 standard, regarding the international evaluation of these parameters, the accuracy is described by two measurement methods: (ISO, 5725-2: 2019). (1) Precision, which refers to the closeness between the results of the test obtained; (2) Accuracy defined as the closeness between the arithmetic measurement of many test results and the accepted reference value.[3]

The combination of both determines the trueness, understood as the reproduction of reality. Accuracy is an important measure to analyze a model from digital impressions. Then, linear portions or the entire arch can be taken and compared with a digital master model.[14] The partial impressions of linear segments of the arch have achieved better accuracy, however, with respect to precision, they can still present some variations, even depending on the acquisition system used.[8,13,15]

Accuracy in dental impressions is a key factor, for example, in the fabrication of dental restorations,[3,6] it has been observed better accuracy in crowns produced from a digital impression compared to those produced from an extraoral scanned model resulting from a conventional impression.[2] This result could be mainly explained by the margins of error in the clinical process of conventional impressions and their subsequent manipulation which can lead to the deformation of the working model. It is key to highlight, the strategy and management of operation of the acquisition apparatus could be the main cause of the discrepancy between the results.[16]

An unpredictable spatial movement of the scanner by the operator would initiate a change in the coordinate system and affect the digital adjustment of the images, consequently reducing the accuracy of the scan.[17] The intraoral scanning strategy used is important in the accuracy of digital impressions.[18,19] During the acquisition process, there are three factors to consider: (1) digital scaffolding, that is, the sequential obtaining of images following an acquisition protocol; (2) legible, well-polished and sharp surfaces to be scanned, and (3) absence of modifying factors such as blood, saliva, and debris.[6,10]

The expansion of digitalization in dentistry has allowed certain workflows to be opened. Open workflows, which allow files to be used among different software, have become a trend. Certain digitizing software such as CEREC SW 4.6.2,[4] after the acquisition through an IOS (Omnicam, Dentsply-Sirona) generates. Stl files which can be exported in different resolutions: low, medium, and high. The resolution of a digital mesh is defined by the number, morphology and regularity of the triangles that conforms it.[20,21] Thus, a .stl file in high resolution will have 100% of the triangles, in medium resolution 75% of the triangles and in low resolution, it will have 25% of the triangles that make up the mesh. There are differences between the digital size of each of the exported files, being bigger for high resolution files, occupying more storage space and slowing down the remote connection process. The possibility of superimposing and correlating different meshes in different resolutions also allows to carry out various comparative studies that generate information that could be useful in the clinical scenario.[16,22–24]

On the other hand, mechanical testing is paramount in restorative dentistry, but its in vivo evidence is limited due to ethical considerations. Virtual models, such as finite element analysis (FEA), have gained popularity since they are able to overcome these ethical limitations and diminish execution costs. One of the main challenges of these virtual models is the ability to mimic three dimensionally the geometrical shape of teeth, which could be overcome with the ability of IOS to acquire great number of details and export these models into widely used formats.

Therefore, the objective of this study is to provide informed and comparative information on the accuracy of exported digital models with the different resolutions available in the CEREC 4.6.2 software obtained by means of an IOS. In addition, establishing differences between meshes, linear and complete arch lengths of different models obtained digitally and their possible usefulness in FEA. The hypothesis is that different resolutions will not differ between them when materialized and when used for FEA.

2 | MATERIALS AND METHODS

The upper complete arch of 10 patients was scanned through an IOS (CEREC Omnicam; Dentsply-Sirona). A standardized scanning protocol was used from the posterior palatal area on one side to the same area on the other side, recovering the occlusal surfaces and incisal edges and then taking the vestibular areas from one side to the other until the model was completed.[17]

The obtained image was exported in low, medium, and high resolution. STL files through CEREC 4.6.2 SW. (Dentsply-Sirona) (Figure 1). A digital mesh was obtained for each type of resolution (Figure 2). The models were prepared in external software (Meshmixer 3.0) by making a flat and hollow base for printing. The resin container bottle was previously shaken for 3 min. Each of the models was printed with resin (Gray resin for dental models, NEXTDENT) through a 3D printer with additive DLP (Sprint Ray MoonRay) technology, with a layer thickness of 50 μm. Once printed, the models were cleaned with 97% isopropyl alcohol and then placed in a light-curing machine for 3 min. In total three printed models were obtained from the IOS in the three types of resolutions available in the software (High, Medium, and Low).

The printed models of the low, medium, and high-resolution files were scanned again, (with the same scanning strategy mentioned above) obtaining 3 digital meshes of the printed IOS model in three types of resolutions.

Once the digital files were obtained, they were grouped according to the type of resolution and scan carried out under the names as shown in Table 1.

Digital analysis and design software for additive manufacturing of prototypes and 3D impressions, (NETFABB Ultimate California, United States/Autodesk/2020) was used to compare the results obtained with the information provided by CEREC 4.6.2 software. To obtain the data, the file was imported into the software. The number of triangulations present in each mesh was quantified according to the chosen resolution. Next, the Imported Parts/Files option was selected, which reflected a screen with the information of the imported file: digital file size, number of triangles and level of detail, which was compared with the information from the manufacturer CEREC

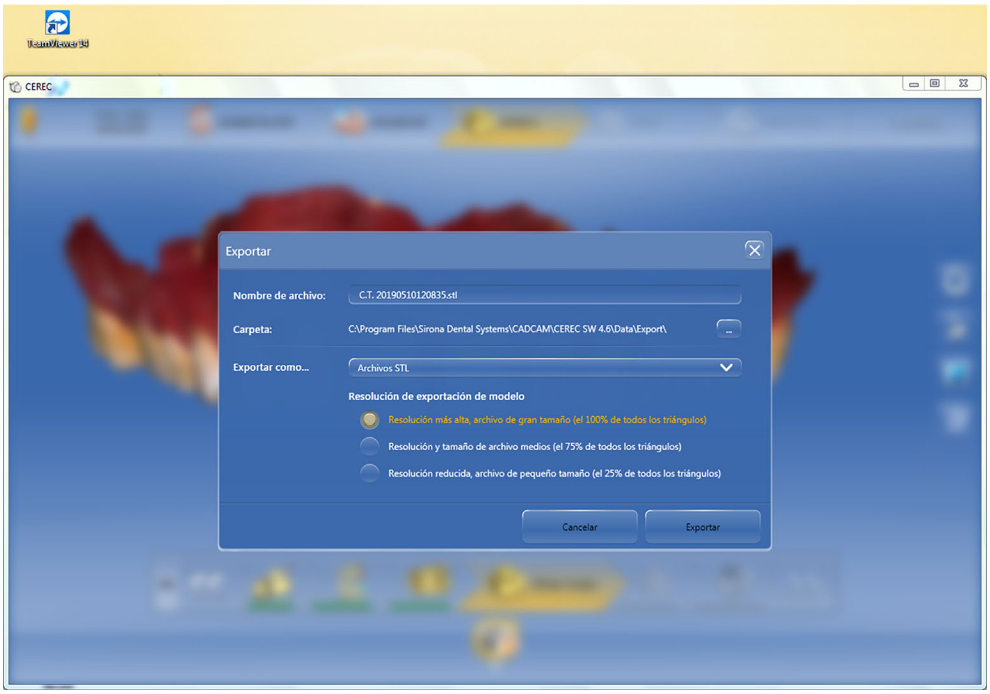

FIGURE 1 Mesh resolution selection in CEREC software

FIGURE 2 Print models from intraoral scanner (IOS) in high, medium, and low resolution

TABLE 1 Denominations of the digital files used in this study

Name	Intraoral scanning High	Intraoral scanning Media	Intraoral scanning Low	Print intraoral scanning High	Print intraoral scanning Media	Print intraoral scanning Low
Denomination	IOSH	IOSM	IOSL	PIOSH	PIOSM	PIOSL

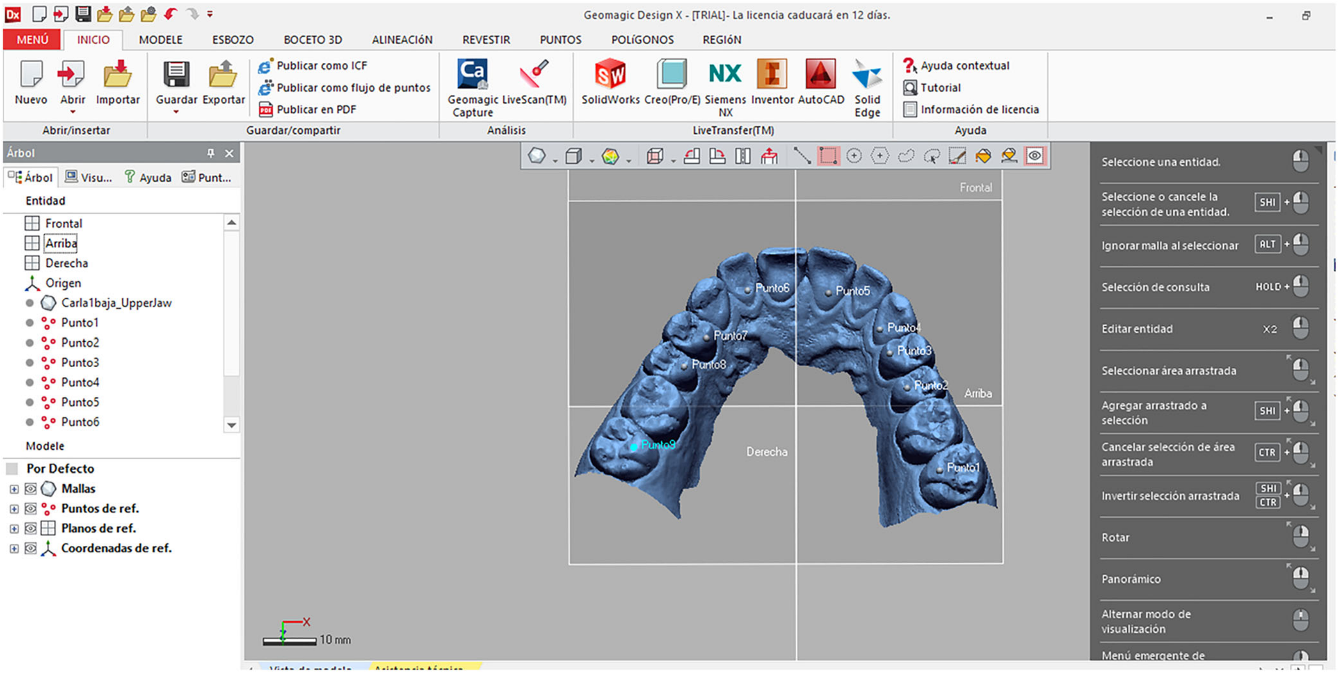

FIGURE 3 Reference points selected to compare the .stl and printed file

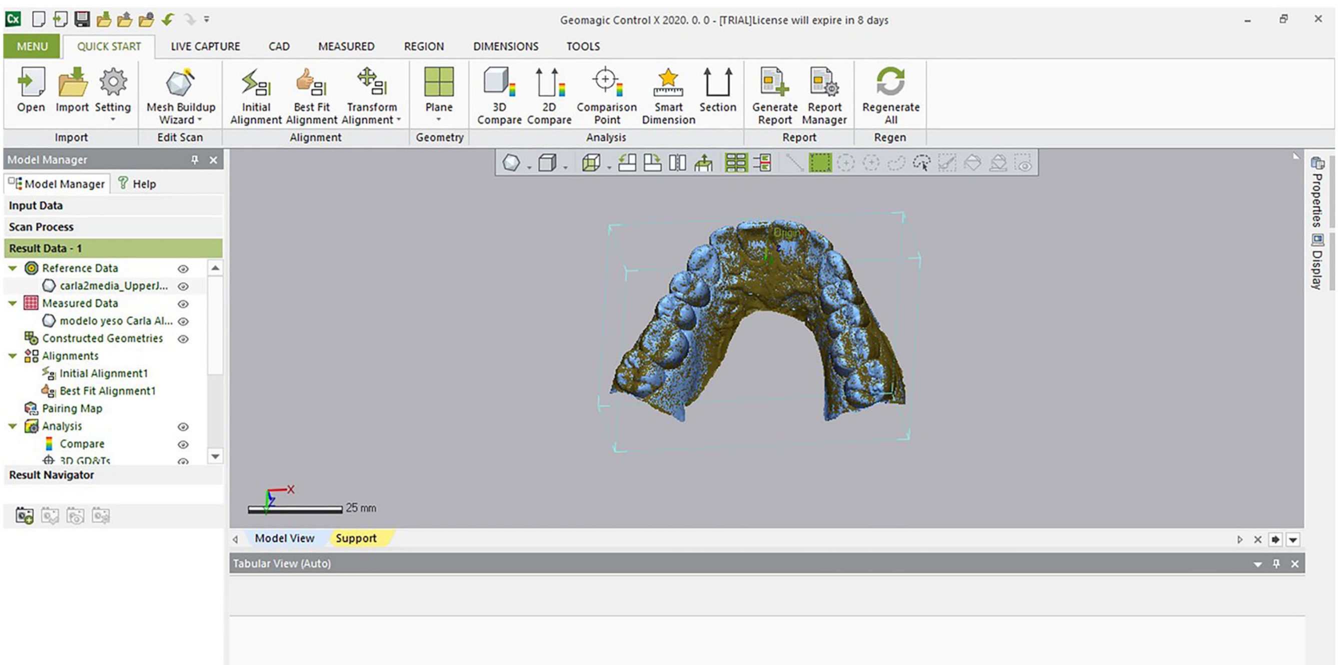

FIGURE 4 Mesh alignment from both objects

4.6.2. (Germany/Dentsply Sirona). Additionally, each of the files were imported at the resolutions available for the IOS models. Subsequently, an intragroup comparison was made between the meshes in the different resolutions.

The selected file was imported into a digital analysis software (GEOMAGIC Control X SW); to standardize the comparison, reference points were placed for matching between the meshes to be compared. The insert function was selected for the reference geometry by visible anatomical points, starting on the right side, anterior and ending on the left side. This was done in the three types of meshes of each one of the acquired files, replicating the same reference points in all, drawing a total of nine reference points (Figure 3). A reference and control mesh (IOSH) were selected to perform the alignment, by right-clicking on it moving it to the reference data for the overlay. Thus, the digital meshes had two references for their alignment: reference points and the digital reference mesh. (Figure 4).

The second selected mesh was then imported to perform the alignment. It started with the initial alignment based on the selected points provided by the Software. Additionally, the Geomagic Control X software (Rock Hill/SC/3D Systems Inc/2020) enhanced alignment analysis tool was selected after initial alignment. Once the digital meshes were aligned, the 3D comparison was started. A window was displayed to determine calculation option: (1) Measurement method: shape. (2) Projection direction: Maximum deviation: 0.05 mm. (3) Display option: color map. (4) Tolerance Range: 0.05 mm. Once these parameters were determined, an image of the meshes aligned with each other reflected through a color map was obtained, where the parameters of accuracy or discrepancies between them were reflected. The software analysis report was generated that would show the discrepancy in percentage of the aligned meshes, expressed in a color map that takes as reference the parameters established in the 3D comparison (Figure 5).

Finally, through the GEOMAGIC Control X software (Rock Hill/SC/3D Systems Inc/2020), the differences between the distances of the reference points of the digital meshes of the IOS for the matching of digital meshes were stablished.

The reference points for taking the plotted measurements were partial 1, teeth 17–14; partial 2, teeth 13–23; partial 3, teeth 24–27 and full arch, teeth 17–27 (Figure 6). The comparisons made were: IOSH versus PIOSH; IOSM versus PIOSM and IOSL versus PIOSL.

2.1 | Finite element analysis

Obtained digital files, with the. STL extension, showed the following file size: High (63,963,284 bytes), Medium (65,829,184 bytes), Low (64,599,854 bytes).

Since these files were surface scans, configured as an external mesh, they were converted to solid bodies, using MeshMixer (3.0), using the following settings:

- Solid type: Accurate
- Solid accuracy: 128 (Cell size 0.611 mm)
- Mesh density: 128 (Cell size 0.435 mm)

These new files were initially analyzed to reveal the strength of the solids, with the Strength Analysis tool (Meshmixer 3.0), applying a standard force in 13 different directions.

The unaltered files were imported into a COMSOL model builder, under the following conditions:

- Definitions: three-dimensional model
- Length unit: millimeters

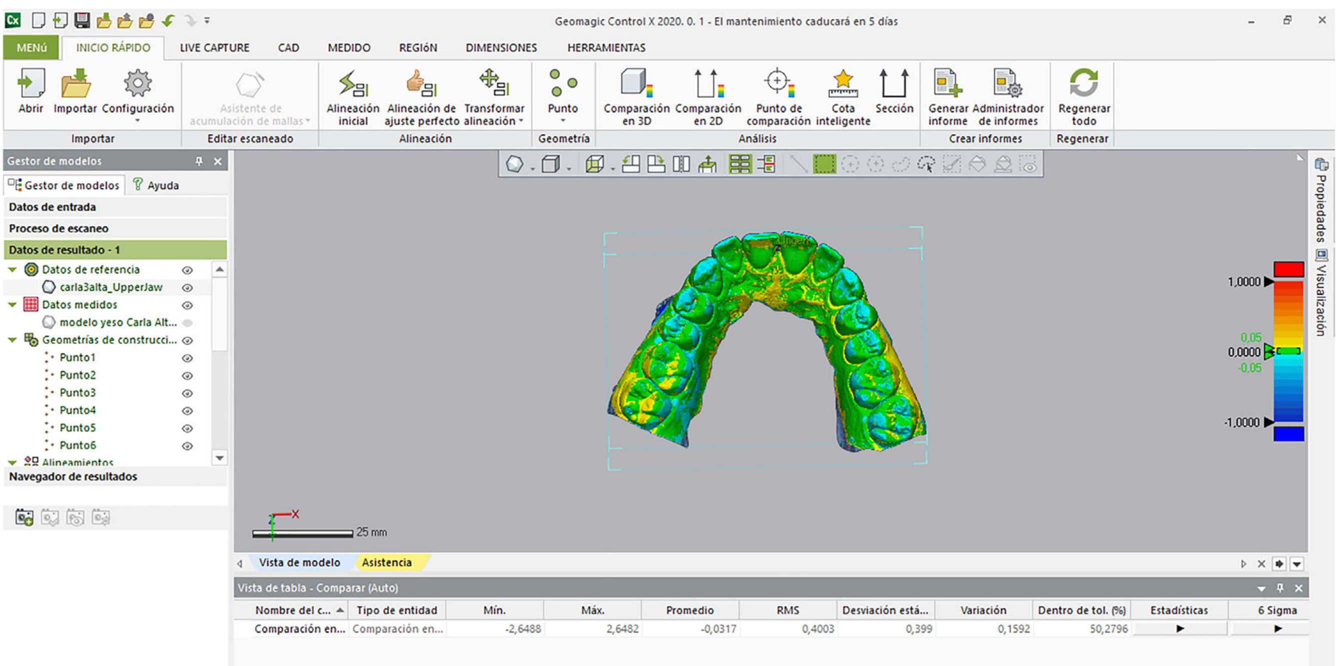

FIGURE 5 3D comparison done in geomagic control

- Angular units: degrees
- Maximum angle within boundaries: 80°
- Minimum relative area: 0.005 mm^2

Since the original scan results delivered a single unit surface, we assigned the material properties of cortical bone to the whole construct (1.7 Gpa Young Modulus, and 0.3 Poison ratio). Once the model was set, we applied forces in six specific occlusal surfaces (Figure 7).

3 | RESULTS

The number of triangles of each one of the meshes is details in Table 2.

3.1 | Finite element analysis

The strength analysis tool from the Meshmixer software showed different force distributions between the three models (Figure 8).

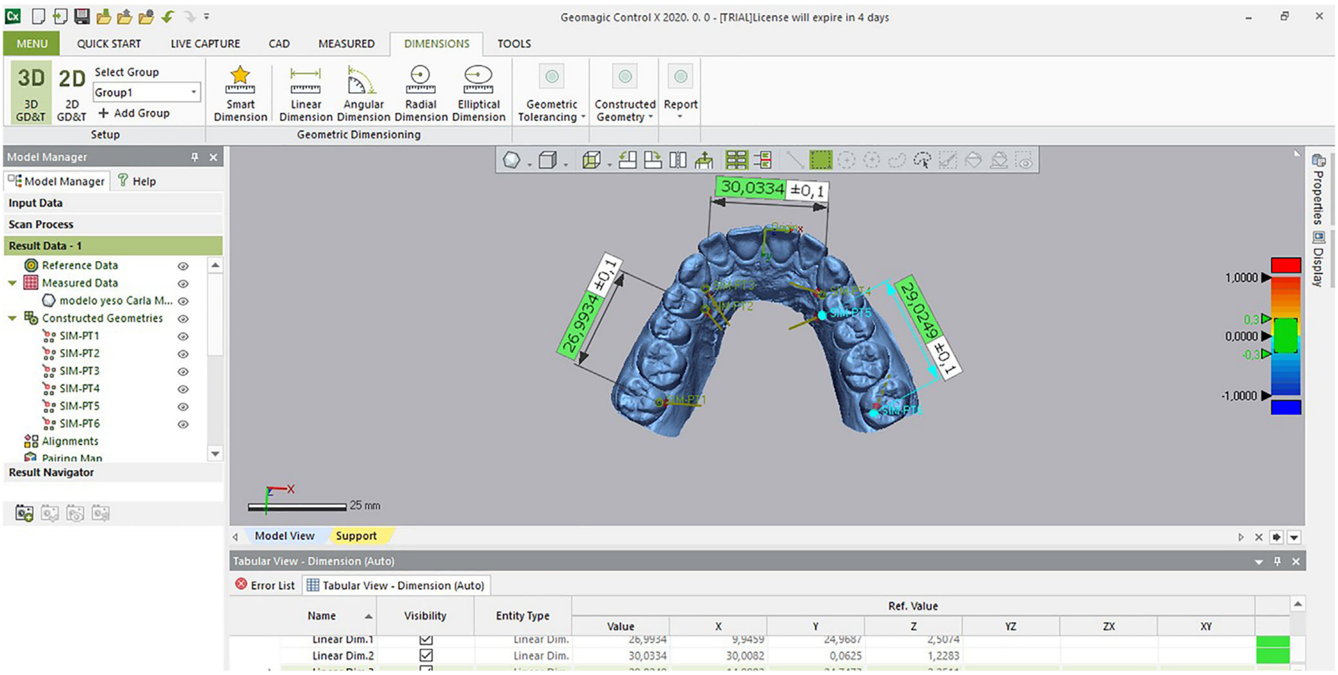

FIGURE 6 Mesh lengths according to the selected reference points

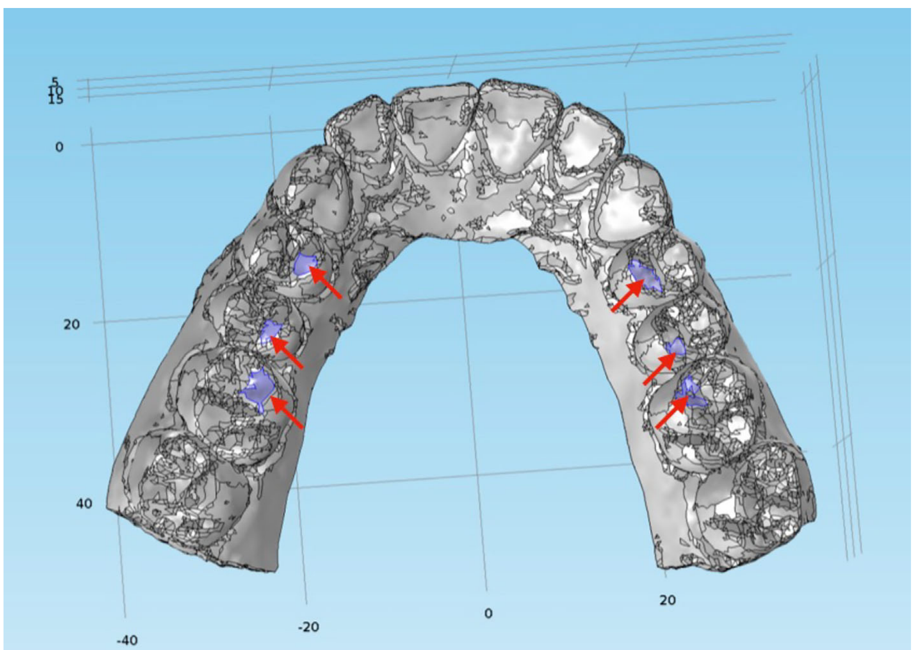

FIGURE 7 Loads applied in the occlusal surfaces of the simulations. The total load applied was 150 N, perpendicular to the occlusal plane. The same surfaces were loaded in all simulations

The three simulations offered converged solutions (Tables 3,4). The stresses were predicted mostly in the loading zones. However, the simulations showed several differences between models, including the number of boundaries and elements of the simulation. These differences are summarized in Table 5.

The force predictions of the three models (Figure 9) shows different results for the three simulations.

Given the equal source and processing of the file, and despite the highly similar file size of three exporting alternative, there are significative differences in the stress predictions for the different resolutions.

4 | DISCUSSION

In this study, files exported in high, medium, and low resolution, from the software of a chairside system coming from an IOS of the same patient were compared in precision and trueness. Through an analysis of the meshes, the number of triangulations present in each digital mesh was quantified; high, medium, and low, comparing it with the information provided by the manufacturer. Number of exported triangles was exact and corresponded to what was previously indicated by the software. Superposition of digital models gives the possibility of comparing them with high trueness and precision.[13] In this study, the accuracy of the models from IOS was confirmed.

Currently, IOS obtain better results compared to conventional impressions of dental preparations, if they are scanned in the absence of blood, saliva, or debris.[2,22] It should be noted, then, that digital impressions obtained from an IOS are preferred to perform restorations through the workflow with a CAD/CAM system.[6,15,21] The highest accuracy of a digitized model is directly proportional to the number of polygonal shapes that can be found in the point cloud.[8] In contrast, some studies affirm that there is no correlation between the number of digital points or polygonal shapes and the accuracy of a digital mesh. However, the accuracy is directly proportional to the quality of a point cloud that a digital model will generate.[11,12] Based on the results of this study, it was determined that the resolution of a digital mesh does not influences its accuracy, showing similar results in a high resolution intraoral digital mesh compared to a low-resolution mesh so the null hypothesis of this study has been accepted. It is important to relate the resolution of a digital mesh with its clinical application. Using a high-density mesh achieves the proper precision for an emergence profile, however a low-density digital mesh can help smooth the margins but decreasing the precision. Many deviations can be found in areas of dental structures with changes in curvature. This may be related to the point cloud density in those areas.[8,15] In digital. stl files, the number, morphology, regularity, and arrangement of the triangles define the resolution of a digital mesh. This does not differ much from the traditional method, in which the plaster model serves as an information store and does not require any prior knowledge of the relative position of each point that makes up the geometry of the object in question. The great advantage of digitization, then, is the ability to constantly reproduce a desired result, controlling the factors that can modify it.[20] The treatment of the meshes in external software could have an influence on the final result. Therefore, the more a clean and flat model can be obtained, the less susceptible to changes.

In the present study, digital mesh alignments were made at different resolutions obtained by the same IOS. Using digital control software, an improved alignment was performed, based on the established reference points and the reference model for mesh alignment. Improved alignments have been previously used in some comparison studies. It has also been shown that point alignments are key in the process.[16,23] Repeated alignments of better fit have been used, for example, to measure errors in the milling process of certain types of restorations. Depending on the clinical applications, multiple anatomical

TABLE 2 Number of triangles of the mesh exported from Cerec SW 4.6.2

Software CEREC SW 4.6.2	IOS	Netfabb resolution (%)
High 100%	759,759 triangles	100
Medium 75%	569,819 triangles	74.99
Low 25%	189,939 triangles	24.99

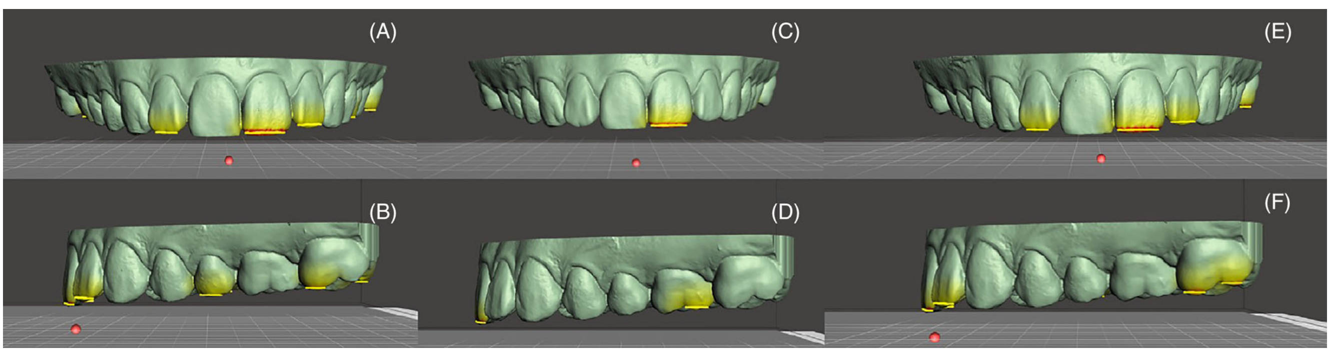

FIGURE 8 (A, B) High resolution/quality. (C, D) Medium resolution/quality. (E, F) Low resolution/quality. Notice the difference of the location of stress concentrations (yellow)

TABLE 3 Digital meshes alignment comparison

Group	Comparison	Minimum	Maximum	Mean	SD
First group IOS	IOSL vs. IOSM	−16.5 um	14.5 um	0.2 um	1.8 um
	IOSL vs. IOSH	−16.4 um	14.7 um	0.1 um	1.8 um
	IOSM vs. IOSH	−4.1 um	3.3 um	−0.3 um	0.5 um
Second group PRINT IOS	PRINT IOSL vs. PRINT IOSM	−12.8 um	11.2 um	0.1 um	2.1 um
	PRINT IOSL vs. PRINT IOSH	−12.4 um	11.5 um	0 um	2.3 um
	PRINT IOSM vs. PRINT IOSH	−4.1 um	3.3 um	−0.3 um	0.5 um
Third group IOS vs. PRINT IOS	IOSH vs. PRINT IOSH	−1.5 um	1.4 um	−0.5 um	0.4 um
	IOSM vs. PRINT IOSM	−0.8 um	0.8 um	0.2 um	0.2 um
	IOSL vs. PRINT IOSL	−1 um	1.3 um	0 um	0.4 um
	IOSH vs. PRINT IOSL	−9.1 um	9.1 um	0 um	2.3 um
	IOSL vs. PRINT IOSH	−9.1 um	9.1 um	0 um	2.3 um
	IOSM vs. PRINT IOSH	−2.2 um	2.2 um	0.3 um	0.5 um
	IOSH vs. PRINT IOSM	−2.1 um	2.1 um	0.3 um	0.4 um
	IOSL vs. PRINT IOSM	−7.2 um	7.2 um	0.2 um	1.7 um
	IOSM vs. PRINT IOSL	−8.5 um	8.5 um	1.5 um	2.1 um

TABLE 4 Mean lengths of the digital model's comparison

Comparison	References 17–14 Differences mean	References 4, 6, 13–20 Differences mean	References 21–24 Differences mean	Complete arch differences mean
IOSH vs. PIOSH	0.02 mm	0.04 mm	0.01 mm	0.00 mm
IOSM vs. PIOSM	0.18 mm	0.24 mm	0.32 mm	0.37 mm
IOSL vs. PIOSL	0.39 mm	0.10 mm	0.48 mm	0.19 mm

TABLE 5 Differences between high, medium, and low quality meshes

Feature	High	Medium	Low
Boundaries	4687	4855	4850
Edges	12,124	12,508	12,566
Vertices	7484	7706	7765
Force applied (N)	150	150	150
Mesh elements tetrahedral	136,882	140,065	142,097
Mesh elements triangular	14,264	30,712	30,834
Surface stress (MPa)	7.95	8.33	9.53

locations of interest were chosen. However, when analyzing the fixed measurement points, the discrepancies of the unmeasured locations were not considered.[14] Although in this study, reference anatomical points were established to standardize the alignment of the samples, the analysis was performed on the entire surface of the aligned digital meshes, allowing obtaining an overall result regarding the discrepancies between them. The distortions observed through the full arch and hemiarch length measurement in this study are consistent with the results obtained by a measurement study. The models obtained from an extraoral scan presented lower values than those obtained from a plaster model.[13] In this study, differences were also found when comparing a digital mesh obtained from an IOS and a digital mesh obtained from the scan of a plaster model, which obtained lower resolution. In another study, the dimensional accuracy of digital models obtained from a cone beam computed tomography (CBCT) scan of impressions in PVS and gypsum models was analyzed. After reconstruction of the digital models, mesio-distal width of each tooth was measured.

The two models were aligned, and no significant differences were found in most of the measurements.[24] Even though the measurement method with a CBCT was different from the present study carried out with an IOS, the differences found in the present study were relevant, in the full arc length. Significant differences in hemiarch length were recorded on a high-resolution IOS digital mesh compared to a low-resolution mesh obtained from a plaster model. Therefore, the resolution of a digital mesh as the source and the information acquisition procedure to generate a digital mesh directly influenced the accuracy of the digital model. It should be mentioned that the resolution of a digital mesh has a relevant influence on the result of the clinical procedure for which it has been exported.

Materialization of digital design is also very important in the accuracy achieved in models originated from IOS. DLP technology for

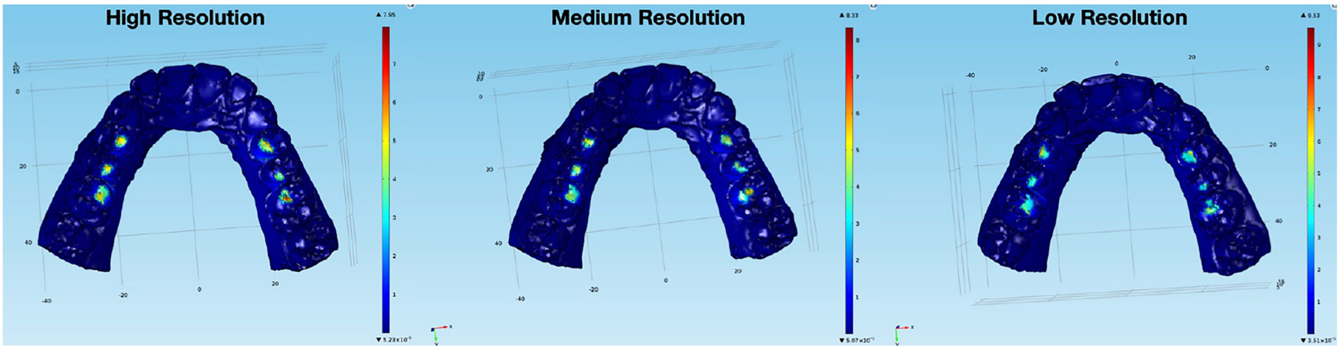

FIGURE 9 Force prediction of the three different quality meshes

materialization, similar to that used in the present study, presents viable characteristics to perform working models in the clinical environment. The post-production processes of the models, once printed, must follow a strict protocol to ensure the greatest possible veracity. Other details such as the presence of hollow bases in the design, such as the one used in this study, should not influence the dimensional accuracy of the models obtained, although the importance of the DLP technology used is confirmed. Although there is evidence that digital models should not entirely replace models obtained through conventional impressions, the results of this study suggest that the type of mesh resolution could be considered in clinical, and laboratory use of the digitally obtained models.

Here we were able to show the potential use of these digital files obtained from IOS into virtual simulations such as FEA. It has been reported in the literature the use of files obtained from micro-computed tomography, which is an expensive obtention methodology and therefore limited compared to the one presented in this article. Further development in the quality of the software and hardware will allow the obtention of higher quality files to improve potential simulations, overcoming limitations and making these methodologies widely available, which would provide meaningful information regarding a wide variety of clinical scenarios. Further research should be done in this area, with focus on specific load and fatigue simulations.

More research studies are recommended regarding the comparison of the materialization systems of digital models. Furthermore, since a limitation of this study was the use of a single IOS, it is necessary to investigate other image acquisition systems.

5 | CONCLUSION

Within the limitations of this study, knowing the differences between 3D printer accuracy on different clinical demands as implant full arch impression, cervical finishing lines for fixed prosthodontics and the applications less demanding as study models, wax-up, surgical guides, occlusal guards, we can conclude that the resolution of digital meshes clinically does not seem influences the dental model accuracy.

DISCLOSURE

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

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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