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ORIGINAL ARTICLE

Analysis of the effects of mesh reduction of digital files on the surface area and volume accuracy of complete dentures using an intraoral scanner

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ABSTRACT

BACKGROUND: The purpose of this study was to determine the accuracy of an intraoral scanner to digitally duplicate complete dentures and analyze the effects of mesh reduction of digital files on the surface area and volume accuracy of complete dentures, in vitro.

METHODS: A mandibular complete denture was scanned by a desktop scanner to create a digital STL reference file (control). Fifteen identical scans were created by using an intraoral scanner and exported as STL files (test group). These 15 files were saved at 100% of the original scan resolution then reduced to 75%, 50%, 25%, and 10% of their original quality. These 75 scans were statistically analyzed by calculating The Hausdorff Distance (HD) and Dice Similarity Coefficients (DSC) to assess the variation between the mean reduced intraoral scanner files test and the control desktop scanner file and eventual inconsistencies. The volumes of the reduced mesh files were also compared with the 100% resolution intraoral mesh files to evaluate precision and trueness of the intraoral scanner.

RESULTS: Reduced mesh files of 10%, 25%, 50%, 75% of the original scan yielded a percentage similarity average of 99.7%, indicating a very high precision value for the intraoral scanner. Also, the volumes of each associated mesh reduction slightly decreased with non-statistically significant results.

CONCLUSIONS: This study concluded that the chosen intraoral scanner for this study provided very high trueness (98.34%) and precision (99.7%), and also the volumes of reduced mesh files slightly decreased but were not statistically significant.

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KEY WORDS: Dentistry; Radiographic image enhancement; Dental impression technique.

Laboratory/desktop scanners are considered to be the most reliable ones to produce an accurate digital scan of complete dentures and full-arch edentulous models.[1, 2] These scanners create accurate scans of cast/dentures by having a scanning table that moves/rotates three-dimensionally to allow for the scanner's light/laser to reach all surfaces without any blockage. However, the downfall of this technology is that most private offices do not have an in-house scanner or laboratory scanner.[3, 4] Laboratory scanner costs, space utilization, and the need for an experienced technician to operate the technology are all challenges that prohibit private offices from integrating this technology into their workflow. A solution to these complications is using intraoral scanners to yield similar results. In recent years, intraoral scanning technology has undergone countless advancements, from its use to scan final impressions for single-unit crowns to multi-unit, long-span FPD (fixed partial dentures).[5-8] These advancements have paved the way for intraoral scanner utilization into other procedural workflows.

Currently, the traditional workflow of denture fabrication is as follows: preliminary impressions, border molding, final impressions, jaw relationship record, trial dentures, and delivery of dentures. It requires at least five patient visits.[9] Also, it can be expected that there will be some processing errors with the final complete dentures and necessary chairside adjustments before delivering them (adding subsequent visits). With the introduction of laboratory scanners and CAD/CAM technology, the complete denture workflow has been improved significantly by reducing the time and materials needed to deliver a final prosthesis.[10, 11] The ability to have/save a digital copy (duplication) of the final complete denture just before delivery is also a benefit to this workflow. It could save the clinician time when fabricating new prostheses and speed up prostheses' delivery to the patient if a complete denture is misplaced, lost, or fractured, laboratory scanner technology has been used to replace the traditional denture workflow to allow for a new set of CAD/CAM complete dentures (same size/contour) to be fabricated if scanned and saved before delivery. This workflow optimization eliminates multiple appointments typically needed to fabricate new dentures. It may even allow a single visit to deliver a replica of a digitally saved CAD/CAM denture. With high-quality scanner technology primarily found in laboratories, dentists have sought out a high-quality intraoral scanner to replicate its results/benefits.

Some private offices have intraoral scanners, mainly used to accurately fabricate single crowns and short-span fixed dental prostheses.[12-14] However, some errors have been reported when intraoral scanners are used for full-arch scans.[15-18] Most intraoral scanners are not able to accurately scan complete dentures (both cameo and intaglio surfaces),[3, 19] a recently available intraoral scanner, Planmeca Emerald S (D4D *et al.*), is now able to scan complete dentures. It is afforded this ability by utilizing red, green, and blue lasers as its light source in conjunction with projected pattern triangulation technology. Once the traditional steps of denture fabrication are completed and the prosthesis has been fabricated, this scanner, a more straightforward and more time-efficient mode of scanning when compared to a standard laboratory scanner, can be used to scan and produce an accurate 'mesh' STL (Standard Tesselation Language) file. This file can be uploaded to Planmeca's proprietary software (Romexis, Planmeca USA Inc, Hoffman Estates, IL, USA) or exported to open-source platforms for digital manipulation and saving.

Digital scanning and digital file saving have several advantages: the slight learning curve for users, cheaper, no physical space is needed for stone-impression materials or to house final casts, and there is no chance for cross-contamination, which is becoming of increasing importance in the age of COVID-19.[20-24] It is recommended that once clinicians obtain mesh files, they are transferred/sent to their dental laboratory for prosthesis fabrication. This transfer step poses a challenge to many clinicians who, out of the frustration of poor internet connection/speed and limited computer specifications, resort to compressing/reducing files before sending them to the laboratory to decrease sending times. Some studies have presented that compressing files can be detrimental to prosthesis fabrication due to file reduction affecting overall accuracy/fit and have even caused some clinicians to abandon this technology.[25-27]

This study aimed to determine the accuracy of an intraoral scanner to duplicate complete dentures digitally and also analyze the effects of mesh reduction of digital files on the surface area and volume accuracy of complete dentures.

Materials and methods

A mandibular complete denture (analog) was scanned by a desktop (laboratory) and an intraoral scanner (Figure 1). The desktop scanner used was the Shape D2000 (Laboratory Scanner, Copenhagen, Denmark), to create a digital file, later used as a reference file. The intraoral scanner (Planmeca Emerald S.D4D Technologies LLC, Richardson, TX, USA), was then used to make identical scans and digital files. Both type of files were exported into a digital STL format that was later reduced and subsequently analyzed for similarity (Figure 2, 3). STL files consist of a given objects surface with a polygon mesh. This mesh is dictated by a three-dimensional Cartesian coordinate algorithm to create an accurate polygonal representation of the scanned object. The size and number of polygons that constitute the mesh are influenced by the scanner's quality.

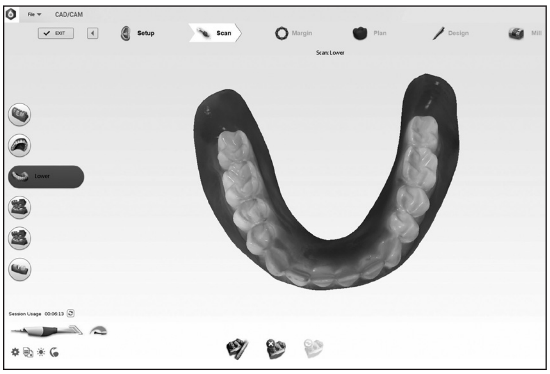

Figure 1.—Occlusal view of the digital scan of complete denture using intraoral scanner.

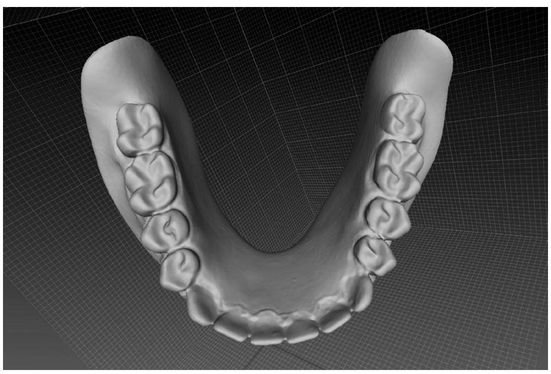

Figure 2.—Occlusal view of the STL file of complete denture from intraoral scanner.

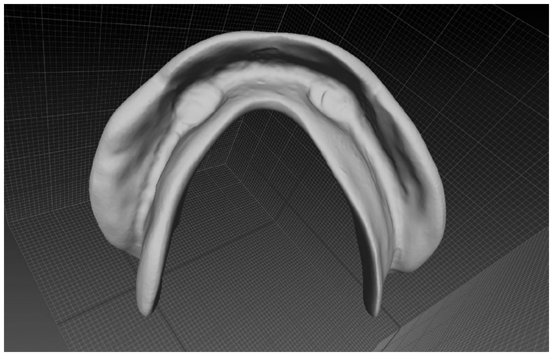

Figure 3.—Internal view of the STL file of complete denture from intraoral scanner.

The more polygons in the file, the larger the file will be. When files are reduced the number of polygons that constitute the scanned object are reduced. The object's overall parameters are kept the same during this process and the result is a file with reduced size.

Using the MeshLab software (Visual Computing Lab, ISTI - CNR, Pisa Italy), files were either kept at maximum quality or reduced then saved. The desktop scan marked as copy "DS100" was unaltered and used as a reference for comparing the reduced files obtained from the intraoral scanner. DS100 represents the highest standard of digital scan, this file's mesh polygons were kept at 100% of its original quality and not subjected to modification. Following, the intraoral scanner was used to scan the prosthesis 15 separate times before the scans were exported as STL files, uploaded to an open 3D point cloud and mesh processing and comparison software (CloudCompare v2.11.3, General Public License of Telecom ParisTech, Paris, France), and saved with the designator "P" and corresponding reduction numeral. Each of the 15 files were kept at 100% of the original quality then reduced to 75%, 50%, 25%, and 10% of their original scan quality. These files were saved as P100, P75, P50, P25, and P10, totaling 75 scans, 15 at each reduction size (Figure 4, 5). Once all files were obtained, the mean of each reduction size category was taken before statistical analysis was conducted.

Considered parameters

The considered parameters were the Hausdorff Distance (HD) and Dice Similarity Coefficients

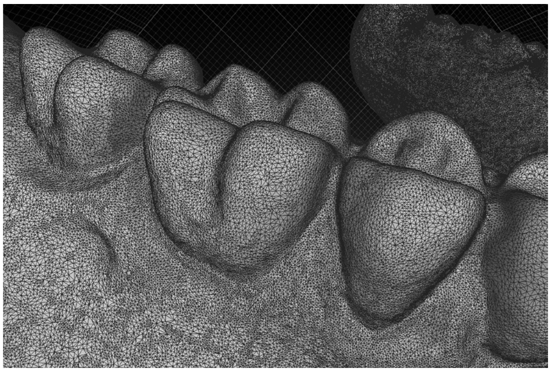

Figure 4.—Mesh file kept at 100% of the original quality, which was labelled as P100. Notice the number/size of triangles available.

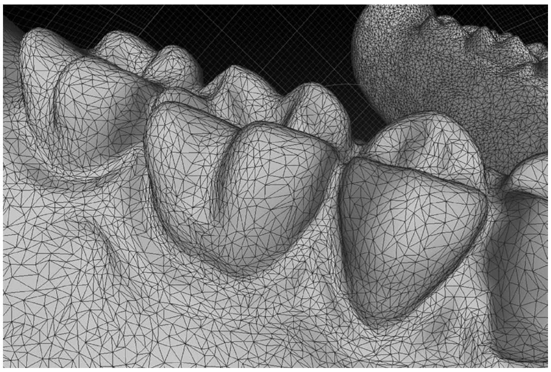

Figure 5.—Reduced mesh file with 10% of the original quality, which was labelled as P10. Notice the number/size of triangles available.

(DSC). HD identifies the same point on identical objects and measures the maximum distance between the two points in relationship to each other. The percentage calculated is then analyzed to determine the similarity and differences of the two objects. This can be visualized by virtually superimposing the objects on the software in two layers to see where surfaces differ from one another. The DSC is then calculated to evaluate the similarities, volumetrically, between the two scanned dentures. This volume-based metric is calculated by evaluating the total overlapping volumes of the two objects when overlain. The numerical value derived from this calculation ranges from 0 to 1 (no overlap to complete overlap). HD and DSC were calculated to quantify the differences between the mean reduced intraoral scanner STL files and the standard DS100 file. Next, the accurateness and precision of the mean reduced Planmeca STL files were compared to the DS100 laboratory scanner file to assess changes/discrepancies.

The HD metric was used to quantify then compare the 3D surface topography of the laboratory and intraoral scanners using approximately 350,000 points., The volume (in cubic units) of DS100 and P100 of fifteen different scans were recorded by using the Measure Volume function of CloudCompare software, under the Mesh menu. The translate/rotate function was used to superimpose the two objects. The Fine Registration (ICP) function was used to align the two meshes with the DS100 as a reference and root mean square (RMS) difference to 1.0e-5 with a 100% final overlap set (Figure 6, 7). The two meshes were then selected to determine the HD using Cloud-Mesh Distance function. The Cork

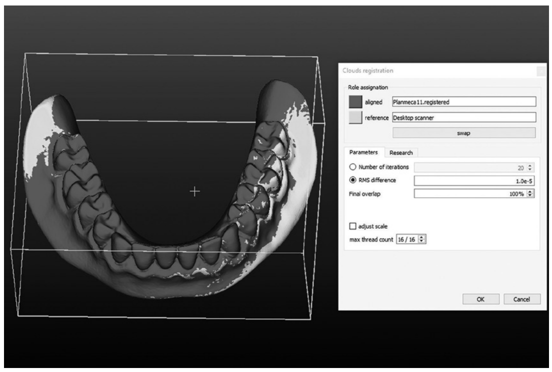

Figure 6.—Virtually superimposing two mesh files (DS100 versus P100) on the software in two layers to see where surfaces differ from one another.

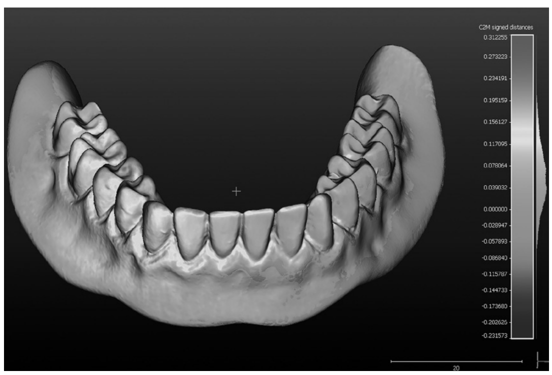

Figure 7.—The DSC was calculated to evaluate the similarities, volumetrically, between the two scanned dentures.

plug-in was used to apply Intersection function to get the intersected mesh. The volume of the intersected mesh was measured to obtain the DSC using the formula below: 2 (intersected mesh volume of DS100 and P100) / (volume of DS100 + volume of P100).

Following the quantitative analysis of HD and DSC, trueness and precisions were considered to determine the clinical significance of the data, indicated by high trueness and precision values. Data with high trueness will demonstrate how similar repeated values are to the known measurement while precision represents how similar the repeated values are to each other. Both trueness and precision are the variables that constitute accuracy, high values in both indicate high accuracy.

Statistical analysis

Statistical analysis was carried out by using the SPSS (v.26.0, SPSS Inc., U.S.A) software. The raw data were tested for normality through the Shapiro-Wilk test. The significance level was set at $\alpha=0.05$. All pairwise comparisons were made using a one-way Analysis of Variance (ANOVA) for independent groups, with a Tukey significance level of 0.05, and Pearson's correlation coefficent. $P<0.05$ was considered to be statistically significant.

Results

In this study, one digital STL file from the desktop scanner (DS100) and also 75 STL files (15 for each resolution; P100, P75, P50, P25, and P10) from the intraoral scanner were used.

The number of vertices, triangles present in the mesh, and the file size were measured in kilobytes. Each metric with the corresponding file reduction is presented in Table I. The volume of DS100 and P100 files (mean value of 15 mesh files) were 14888.40 mm³ and 15236.45±114.67 mm³, with a percentage similarity of 98.34% (Table II), indicating a very high trueness value for the intraoral scanner.

When the volumes of mesh files with different resolutions (P75, P50, P25, and P10) were

TABLE I.—*Mean±standard deviation percentage reduction (%) of 3D mesh and associated polygon parameters.*

Group	Mesh %	Number of vertices present in the mesh	Number of triangles present in the mesh	STL file size (Mb)
P100	100	345088.93±3417.34	690320.93±6695.95	32.87±0.33
P75	75	258900.27±2509.06	517740.67±5021.91	25.30±2.58
P50	50	172400.67±1732.61	344758.20±3467.61	16.40±0.16
P25	25	86285.33±856.56	172529.27±1711.81	8.23±0.07
P10	10	34526.00±335.56	69029.67±670.65	3.30±0.04

TABLE II.—*Comparison of mean±standard deviation volume, Hausdorff distance (HD), Dice similarity coefficient (DSC) between Desktop scanner (DS100) and Planmeca at full detail (P100), and overall percentage similarity.*

Group	Volume (mm³)	HD (mm)	DSC	Percentage similarity [a]
DS100	14888.40	0.05103±0.0146	0.98343±0.0032	98.34%
P100	15236.45±114.67			

[a] % Similarity obtained by multiplying DSC by 100.

TABLE III.—*Comparison of mean±standard deviation volume, Hausdorff distance (HD), Dice similarity coefficient (DSC) between Planmeca at full detail (P100) and Planmeca at 75% (P75), 50% (P50), 25% (P25), and 10% (P10).*

Group	Volume (mm³)	HD (mm)	DSC	Percentage similarity
P100	15236.45±114.67	0.000033±0.000004	0.999917±0.000034	99.99%
P75	15219.96±92.96			
P100	15236.45±114.67	0.000142±0.000004	0.999851±0.000084	99.99%
P50	15219.62±93.05			
P100	15236.45±114.67	0.000434±0.000010	0.999709±0.000195	99.97%
P25	15219.11±93.16			
P100	15236.45±114.67	0.011154±0.000015	0.999407±0.000295	99.94%
P10	15215.51±94.40			

Table IV.—*Surface areas (mean±standard deviation) of mesh files from P10, P25, P50, and P75 are highly correlated with P100 with a value of 0.999.*

Group	Mean surface area (mm^2)	Pearson's correlation coefficient (r)
P100	7501.83±16.71	0.999
P75	7501.88±16.70	
P100	7501.83±16.71	0.999
P50	7502.08±16.20	
P100	7501.83±16.71	0.999
P25	7502.86±16.76	
P100	7501.83±16.71	0.999
P10	7504.83±16.68	

compared to that of the mesh file of P100, percentage similarity values ranged from 99.9% to 99.4% (average of 99.7%) (Table III), indicating a very high precision value for the intraoral scanner. Also, when resolutions of the mesh files were reduced, the volumes of mesh files slightly decreased but these differences were not statistically significant.

In addition, when surface areas of mesh files for each resolution were compared, statistically significant correlations (r=0.999) were noted at any given percentage reduction (Table IV), indicating a very high precision value for the intraoral scanner. Moreover, when resolutions of the mesh files were reduced, the surface areas of mesh files very slightly increased but these differences were not statistically significant.

Discussion

The innovation technology has always characterized through history the dental sciences involving the dental industry, clinicians and technicians, s to enhance patient/clinician experiences. The integration of intraoral scanner technology to supplement or even replace the use of desktop scanners is no exception.[26-28] While previous technology has limited the use of intraoral scanners to mainly single-unit prosthesis and short-span fixed dental partial prostheses, new advancements in this technology are allowing for expanded functions to be explored.

The practice of intraoral scanners being used for full-arch scans and long-span prosthesis is mainly limited by their ability to generate accurate surface topography of scanned surfaces.[29, 30] In this study, the Planmeca Emerald S scanner provided an accurate and predictable way to scan and create digital files of complete dentures (an item significantly larger than its intended use). The scanner was able to accurately scan, compared to the standard desktop scanner, a complete denture with 98.34% similarity. This data, in addition to a mean±standard deviation volume of 15236.45±114.67 (mm^3), Hausdorff distance 0.05103±0.0146 (mm), and a Dice similarity coefficient 0.98343±0.0032 compared to the desktop scanner show an increase in development/accuracy of intraoral scanning technology when scanning complete dentures. These data points show that intraoral scanners will be able soon to tackle larger, more complex restorative procedures.

Studies validating this suggestion are limited and to make a valid conclusion more studies in this topic should be conducted.

Additionally, this study proves that the reduction of file size from the original scan size pose a negligible variance of the final digital product when scanning a large prosthesis such as complete dentures. On a smaller scale (single-unit prosthesis)[25] it had previously been understood that a reduction in the digital size could result in a reduction of quality of the final restoration, and discrepancies on the intaglio and margin surfaces. This thought process is inconsistent with the outcomes of our complete denture study which suggest that the difference between an original intraoral scan using the Planmeca Emerald S and its reduction to 10% of original size had an overall 99.94%. Concluding that for larger restorations the same principals do not apply.

Each intraoral scanner manufacturer uses proprietary technology to capture a digital replica of an intended object which inherently makes all intraoral scanners different. Our study depicts the use of one specific intraoral scanner that yielded the above results. Furthermore, there are available several digital software/algorithms (Meshlab, MeshMixer, Geomagic, etc.) to process/alter digital files, which also make each file produced different.[31, 32] These incongruities are also noted when fabricating the final process (via 3-,4-,5-axis milling, 3-D printing, etc.), with alterd final outcomes. It is crucial the clinician is aware that understanding each segment of his/her workflow is paramount for accurate outcomes and that our study highlights a specific workflow.

A study by Farook *et al.*,[25] investigated mesh optimization by using a software program in various prosthodontic applications. They fabricated an auricular prosthesis, a complete denture, and anterior and posterior crowns by using conventional methods and laser scanning to create computerized 3D meshes. The meshes were optimized with 4 software programs to 100%, 90%, 75%, 50%, and 25% levels of original file size. They noted differences in vertices, file size, surface area, and volume. The choice of software significantly influenced the overall virtual parameters of auricular prosthesis and complete denture across optimization levels. However, interpoint discrepancies were smaller than 0.1 mm and volumetric similarity was >97%. They concluded that software programs used in their study could optimize smaller dental prostheses without greatly influencing dimensional parameters.

A study by Lee *et al.*,[35] evaluated the surface topography and the precision measurements of various intraoral and extraoral scanners by examining digital impressions of a maxillary arch with four implant analogs. The maxillary arch was scanned 15 times with 3 different intraoral and 2 different extraoral scanners. They examined the surface topography and obtain same quadrant and cross-arch precision measurements by using a software program. They have concluded that scanning resolution does not correlate to the precision and reproducing the surface topography does not depend on the anatomical tooth structure and position.

Conclusions

Within the limitations of this study, the following conclusions were drawn:

1) The intraoral scanner used in this study provided very high trueness (98.34%) and precision (99.7%) values.

2) When resolutions of the mesh files were reduced, the volumes of mesh files slightly decreased but these differences were not statistically significant.

3) When surface areas of mesh files for each resolution were compared, no statistically significant correlations were noted at any given percentage reduction.

Although there are no significant differences observed in our study, the authors do not recommend compressing files because it may still pose risk for inaccuracy.

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Conflicts of interest
The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Authors' contributions
All authors read and approved the final version of the manuscript.

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