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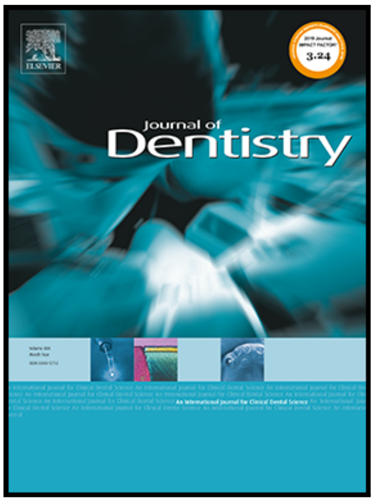

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Title: Triangular mesh reduction of digitized maxillectomy defects for prosthetic rehabilitation: A 3D deviation study

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Mahmoud E. Elbashti: Conceptualization, Methodology, Resources, Formal analysis, Writing-Original draft preparation, Supervision.

Amel Aswehlee: Resources, Formal analysis, Writing- Original draft preparation.

Marwa Abdel Rahman: Resources, Formal analysis, Writing- Original draft preparation.

Yuka I. Sumita: Resources, Writing - Review & Editing.

Michael M. Bornstein: Writing - Review & Editing.

Martin Schimmel: Resources, Writing - Review & Editing.

Samir Abou-Ayash: Methodology, Writing - Review & Editing.

Pedro Molinero-Mourelle: Methodology, Resources, Formal analysis, and Project administration.

ABSTRACT

Objectives: To evaluate the effect of different amounts of triangular mesh reduction on the trueness of digitized complete-arch dentate and edentulous maxillectomy defects models.

Material and Methods: Twenty gypsum maxillectomy defect models (dentate and edentate group: n=10) were digitized using the Trios 3 intraoral scanner, scanning the teeth, mucosa and maxillectomy defect. These datasets (reference, R_0) were saved as standard tessellation language (STL) files, and triangular mesh reduction was performed using Meshmixer's reduction tool. Digital test-datasets with file sizes reduced by 50%(R_1), 75%(R_2), and 90%(R_3) were generated (each: n=20). Each test-dataset was compared to the R_0 file using 3D evaluation software (GOM Inspect), applying automated pre-alignment followed by a global best-fit alignment, and root mean square (RMS) 3-dimensional (3D) deviations were calculated. Statistical analyses were performed, at a level of significance of α=0.05.

Results: The number of triangles, and STL file size were synchronized with each other and inversely proportional to the amount of mesh reduction. The resulting mean percentages of the STL file sizes were 50.00% for R_1, 24.93% for R_2, and 10.00% for R_3. There were no 3D deviations at 50% triangular mesh reduction. The 3D deviations increased with the amount of mesh reduction: at 75% reduction the median deviations were lower (dentate:0.0016mm, IQR:0.0015-0.0018; edentate:0.0016mm, IQR:0.0015-0.0016), than at 90% (dentate:0.004mm, IQR:0.0038-0.0041; edentate:0.003mm, IQR:0.0036-0.0039). A statistically significant increase in 3D deviations was observed with higher degrees of mesh reduction ($p<0.001$).

Conclusions: Triangular mesh reduction results in a significant increase in 3D deviations if the reduction is more than 75%.

Clinical Significance: Digital models of patients with maxillectomy defects can be saved with a mesh reduction of 50% without affecting the trueness. The use of a 50% mesh reduction decreases the required storage capacity by 50%.

Keywords: Maxillectomy; triangular mesh reduction; 3D deviation, trueness; digitization

1. INTRODUCTION

Congenital and acquired intraoral defects for maxillofacial prosthetic rehabilitation can be digitized either directly, using intraoral scanners alone [1, 2], or combined with medical imaging such us cone beam computed tomography or computed tomography [3-8]. On the other hand, this process can also be conducted indirectly by scanning a conventional impression or master cast using desktop scanners [9-11]. Either way, a large data file size is generated as a result of three-dimensional (3D) reconstruction of the scanned objects.

The 3D reconstruction process generates polygon meshes, which are a collection of triangle-shaped polygons that define the geometry of the scanned object. The shape of the polygon mesh varies depending on the density of the respective triangles. Thus, a higher density of triangles represents a more detailed 3D model of the defect known as resolution can result in higher accuracy for prosthesis design [12]. However, a large number of triangles results in certain drawbacks, such as increasing the file size, which requires higher computing power, more effort and manipulation time, and also more storage capacity.

An alternative approach to using powerful computing systems is to use a mesh optimization approach which is the process of reducing 3D models to minimize storage file size and computational load [13]. This may raise the concern of trueness which is defined as the closeness match between a test dataset and a reference dataset and is measured as potential deviation between the two datasets. Due to the rapidly increasing use of open-sourced modeling and designing software, recent studies [13, 14] have assessed the percentage of mesh reduction for the design of intraoral digital obturators and other extraoral maxillofacial prostheses. However, the literature is scarce in studies evaluating and comparing the effect of triangular mesh reduction on the 3D deviations for native digitized models of dentate and edentulous maxillofacial defects. Therefore, this study is aimed to evaluate 3D deviations following a series of triangular mesh reduction processes for 3D models of dentate and edentulous maxillectomy defects. More specific, to investigate the relationship between trueness and resolution of the digitized maxillectomy models. The null hypothesis was that the trueness of the 3D model would not be affected by different percentages of triangular mesh reduction processes and the dentation status.

2. MATERIALS AND METHODS

2.1 3D data acquisition and modeling

The sample size (n=10 per group) was estimated by a sample size analysis, assuming statistical significance ($\alpha = 0.05$) with a power of 0.95 based on data from a pilot study. Twenty gypsum models of classes I, II, and IV of Aramany's classification [15] for maxillectomy defects (dentate group n=10 and edentulous group n=10) were selected from the patients' gypsum models at the XXXXXXXXXXXXXXXX. The models were digitized using the Trios 3 intraoral scanner (3Shape, Copenhagen, Denmark) (Fig. 1). All scans were scanned by one operator (ME) and performed under the same condition in the same room, which excluded the influence of extraneous light and was maintained a constant temperature (mean temperature 22°C ±1°C). The scanning procedure started at the occlusal surfaces of the posterior teeth moving toward the anterior teeth in a zigzag pattern and then the buccal and the palatal surfaces were scanned in the same manner. The scanner tip was then moved to scan the mucosal region including the palate and the maxillectomy defect.

The scanned data were saved as standard tessellation language files (STL format). All STL models were imported to Autodesk Meshmixer (Autodesk, Inc. CA), the 3D modeling software for data editing and reduction. To trim and isolate unwanted scanned data, the select function followed by smooth boundary and discard was used. The triangular mesh reduction process was performed for each STL model (reference, R_0) using the Meshmixer software reduction tool, generating reduction percentages of 50% (R_1), 75% (R_2), and 90% (R_3) of the total data size of the reference models. A total of 80 STL models were produced.

2.2. 3D data evaluation

The total number of triangles, vertices, the STL file size (KB), and the triangle quality depending on shape and aspect ratio for R_0, R_1, R_2, and R_3 were calculated using MeshLab software (MeshLab; Visual Computing Lab, ISTI-CNR, Pisa, Italy) (Table 1) (Figs. 2a-2d). To determine the trueness, R_0 was used as a reference dataset, and the reduced triangular mesh datasets R_1 to R_3 were used as test data. The test datasets were geometrically evaluated and compared to the reference data using 3D evaluation software (GOM Inspect, GOM GmbH, Braunschweig, Germany). An automated pre-alignment followed by a global best-fit alignment process was used to superimpose the datasets. The software calculated the total differences in absolute 3D deviations using the root mean square (RMS), which represents the approximate distance between all surface points of the superimposed reference model and the test model (Fig. 3).

2.3. Statistical analysis

An ATS-type ANOVA statistical analysis was performed to assess if there were any changes in trueness as the relative mesh reduction increased and whether these changes were similar in the two groups (dentate and edentulous). The Mann-Whitney test was used to compare the distribution of deviation values between the two groups at each of the reduction settings. The significance level used in the analysis was 5% ($\alpha = 0.05$).

3. RESULTS

The mean ±SD of the total number of triangles in dentate models for R_0, R_1, R_2, and R_3 were 896120.80 ±154101.68, 448060.80 ±77051.31, 224030.60 ±38526.22, and 89612.60 ± 15411,09, respectively. While in edentulous models they were 607187.90 ±109068.64 for R_0, 303594.00 ±54534.78 for R_1, 151796.40 ±27267.42 for R_2, 60718.20 ±10906.93 for R_3. Table 1 presents the detailed results.

There were no 3D deviations in both dentate and edentulous groups at 50% triangular mesh reduction (0.0000 mm). There were minor 3D deviations at 75% reduction in both dentate (median 0.0016 mm, IQR: 0.0015-0.0018) and edentulous models (median 0.0016 mm, IQR: 0.0015-0.0016). At 90% reduction, there were higher 3D deviations in both dentate (median 0.0040 mm, IQR: 0.0038-0.0041) and edentulous groups (median 0.0037 mm, IQR: 0.0036-0.0039) (Table. 2).

A statistically significant increase in 3D deviations was observed along the increase in the degree of mesh reduction ($p < 0.001$). However, this increase varied according to the group (dentate and edentulous). The overall differences in the 3D deviation values of both dentate and edentulous groups were close to statistical significance ($p = 0.079$), and particularly depended on the level of reduction being analyzed ($p = 0.047$). The Mann-Whitney tests revealed that there were no significant differences at both 50% and 75% reductions (*p* = 1,000 and *p* = 0.393, respectively). In contrast, a significant difference was found at 90% reduction (*p* = 0.035) (Table. 2).

The number of triangles, vertices, and STL file size were synchronized with each other and were inversely proportional to the percent of mesh reduction in both dentate and edentulous models. In particular, the final mean percentages of the STL file sizes were 50.00% for R_1, 24.93% for R_2, and 10.00% for R_3.

4. DISCUSSION

The 3D deviations of digital maxillectomy defect models showed a variety of trueness levels depending on different percentages of triangular mesh reduction and the dentation status. Although the effect of mesh reduction on trueness was small, the null hypothesis was rejected. The triangular mesh reduction of complex 3D models is important for smooth performance of modeling and design software within the digital workflow [16]. High trueness of the reduced meshes of complex maxillectomy defects is also essential to achieve a properly fitting prosthesis. The reduction process is mainly based on merging a group of small neighboring triangles into a single larger triangle, which influences the geometry of multi-angular and curved surfaces rather than flat geometries. Consequently, a higher reduction percentage results in greater numbers of small triangles merged within a single larger triangle.

The results of this study showed that the file size measured in kilobytes has an almost uniform reduction size as a result of reducing the total number of triangles and vertices. For instance, a fifty percent mesh reduction could save about 50% of the available storage capacity without any concern for inaccuracy. This reduction in STL file size is important in the clinical setting, as these 3D data can be stored in either disk space or in cloud space with less needed storage capacity. However, a significant increase of the deviations with increasing mesh reduction could be seen. It may be assumed that the deviations of 4 µm, as indicated by the upper limit of the interquartile ranges in the R3 group, are clinically negligible, especially when considering the deviations of about 100 µm indicated for removable partial and complete denture manufacturing [17, 18]. Although additional software, further steps, and time are needed, Meshmixer for example is free software that can be used at no extra cost. In general, triangular mesh reduction can effectively reduce the total file size which could improve the computational load and performance of the modeling and design software as well as save additional storage capacity. Comparing these results to other studies, Farook et al. [13] have evaluated the influence of software and optimization on surface area and volume of various maxillofacial prostheses, including complete dentures. They found that ear prostheses had the largest differences in virtual surface area and volumetric parameters and attributed this finding to the complex anatomy. This may also be the reason for the higher deviations found in the dentures in the edentate group of the present study since those include small anatomical details which could have been lost during mesh optimization. Peroz et al. studied the effect of mesh density when using intraoral scanners [19]. They were able to show a more significant effect of mesh density on trueness than in our study. This may be attributed to the use of reference bodies to determine the deviations in that study, rather than measuring deviations along with the entire model.

Pre-alignment followed by global best-fit alignment was used to superimpose the analyzed datasets, as applied in many previous studies [20, 21]. It has been shown, that obtaining perfect alignment is challenging with digital comparison software especially when evaluating a complex structure such as a maxillofacial defect. Several alignment approaches have been used including landmark-based alignment, global best-fit alignment, also termed iterative closest point alignment, and a reference best-fit alignment for digital data comparisons [19, 21]. O'Toole et al.

[21] have assessed the accuracy of the most commonly used alignment techniques and their impact on measurement metrics. They found that reference alignment produced significantly smaller alignment errors and truer measurements. Global best-fit and landmark-based alignment significantly underestimated the defect size. However, in the present study, a global best-fit alignment was used to assess trueness. It was used because the entire model area is important in maxillectomy patients, it does not involve operator-based decisions, and operator error can be avoided when selecting landmarks for landmark-based alignment or sections for reference alignment. In the present study, trueness was analyzed by calculating RMS values, which is a commonly used method [21, 22]. However, recent studies have shown that calculations such as absolute average value, and (90-10)/2 percentile result in significant differences when compared with RMS values while evaluating the trueness [23, 24]. Lerner et al. [23] reported similar results for RMS and 90-10/2 methods, while significantly smaller deviations were found using the absolute average values. However, the 90-10/2 method, eliminates the highest and the lowest 10% of point deviations, which could be especially critical analyzing meshes that underwent a point reduction, due to possible underestimation of the inaccuracies. Consequently, the RMS evaluation was applied in the present study, as since it should represent the worst possible result when applying triangular mesh reduction, which is most relevant when assessing feasibility.

In the present study, dentate maxillectomy defect models showed greater 3D deviations, especially when the reduction percentage is higher than 75%, whilst whereas edentulous models revealed smaller deviations. This could be due to the fact that the dentate models (particularly teeth) are multi-angular and present curved geometries, resulting in a large number of smaller triangles [25]. Thus, higher levels of reduction generally produce a flatter geometry, which affects the trueness (Fig. 4). The results of the present study agree with a study carried out by

Farook et al [14], who found that mesh reductions of up to 75% can be applied when designing intraoral maxillofacial prostheses, without significantly affecting the volumetric or geometric properties of the prostheses.

Although this study is limited to only dentate and edentulous maxillectomy defects, further research is needed to evaluate the 3D deviation linked to triangular mesh reduction for extraoral maxillofacial defects. The variety in of tissue structures and complexity, digitizing resources, data sizes, and density may result in different triangular mesh reduction values. Another limitation is that the present study focused on maxillofacial prosthetics field, there are other scenarios, such as fixed prosthodontics where the resolution of the 3D reconstruction is key to achieve adequate trueness. Nedelcu et al, [26] have analyzed the level of finish line distinctness, and finish line accuracy in 7 intraoral scanners and one conventional impression. They also assessed resolution, tessellation, topography, and color parameters. They found that Trios 3 presented the highest finish line distinctness, and finish line accuracy. It also had the highest resolution by factor 1.6 to 3.1 among other intraoral scanners evaluated. They concluded that high finish line distinctness was more related to high localized finish line resolution and non-uniform tessellation, than to high overall resolution. In addition, although each intraoral scanning system has its own output data resolution, only one intraoral scanning system (Trios 3) was used in the present study which represents one reference mesh resolution. Other intraoral scanning systems may have different 3D modeling processes for the scanned data which may produce 3D models with higher or lower resolutions. However, it is an advantage that Trios 3 was used in this study as it has the highest resolution by factor 1.6 to 3.1 among common intraoral scanners [26]. Furthermore, indirect digitization can be obtained by scanning the impression or the stone model using a laboratory scanner which produces higher resolution data. Therefore, future studies are recommended to explore the performance of different intraoral scanning systems and laboratory scanners. Moreover, Meshmixer was used along with Meshlab in this study as editing and reduction software. These software are not certified as class IIA (CE) nor class II (FDA) for clinical use which can be considered as another limitation for this study.

5. Conclusions

Within the limitations of this study evaluating only maxillectomy defect models, focusing solely on maxillofacial defect models, and using only one intraoral scanning system, the effect of triangular mesh reduction for 3D models of maxillectomy defects on trueness of 3D deviations was evaluated. It was found that 50% mesh reduction on maxillofacial defect models resulted in no difference in terms of deviation compared to non-reduced datasets. Practitioners can perform triangular mesh reductions up to 90% of the native digitized data to reduce computational load with only minor additional inaccuracies. However, high data reductions can have a significant impact on the trueness of the digitized models.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table. 1. Represents mean ±standard deviation of triangles, vertices, and STL file size for native and tested data of different triangular mesh reduction percentages for both dentate and edentulous maxillectomy defects.

3D Models	Mesh Reduction (%)	Dentate				Edentulous			
		No of Models	No of Triangles (Mean ±SD)	No of Vertices (Mean ±SD)	STL file size (KB) (Mean ±SD)	No of Models	No of Triangles (Mean ±SD)	No of Vertices (Mean ±SD)	STL file size (KB) (Mean ±SD)
R_0	(0%)	10	896120.80 ±154101.68	449162.90 ±77174.81	43756.40 ±7524.36	10	607187.90 ±109068.64	304466.50 ± 54586.75	29648.50 ±5325.76
R_1	(50%)	10	448060.80 ±77051.31	225132,80 ±38650.44	21878.80 ±3761.84	10	303594.00 ±54534.78	152669.20 ± 27319.54	14824.60 ±2662.81
R_2	(75%)	10	224030.60 ±38526.22	113117.70 ±19389.62	10912.60 ±1929.91	10	151796.40 ±27267.42	76770.40 ± 13685.99	7412.50 ±1331.32
R_3	(90%)	10	89612.60 ±15411,09	45908.70 ±7838.16	4376.00 ±752.65	10	60718.20 ± 10906.93	31231.30 ± 5506.11	2965.30 ±532.47

SD, standard deviation; STL, standard tessellation language; KB, kilobytes.

Table. 2. Represents 3D deviations for tested data of different triangular mesh reduction percentages for both dentate and edentulous maxillectomy defects.

3D Models	Reduction (%)	Dentate			Edentulous			*P* value
		N	Median	IQR	N	Median	IQR	
R_1	(50%)	10	0.0000	0.0000-0.0000	10	0.0000	0.0000-0.0000	1,000
R_2	(75%)	10	0.0016	0.0015-0.0018	10	0.0016	0.0015-0.0016	0.393
R_3	(90%)	10	0.0040	0.0038-0.0041	10	0.0037	0.0036-0.0039	0.035*

N, number of models; IQR, interquartile range; R, reduction; * Significant at P<0.05.

FIGURES

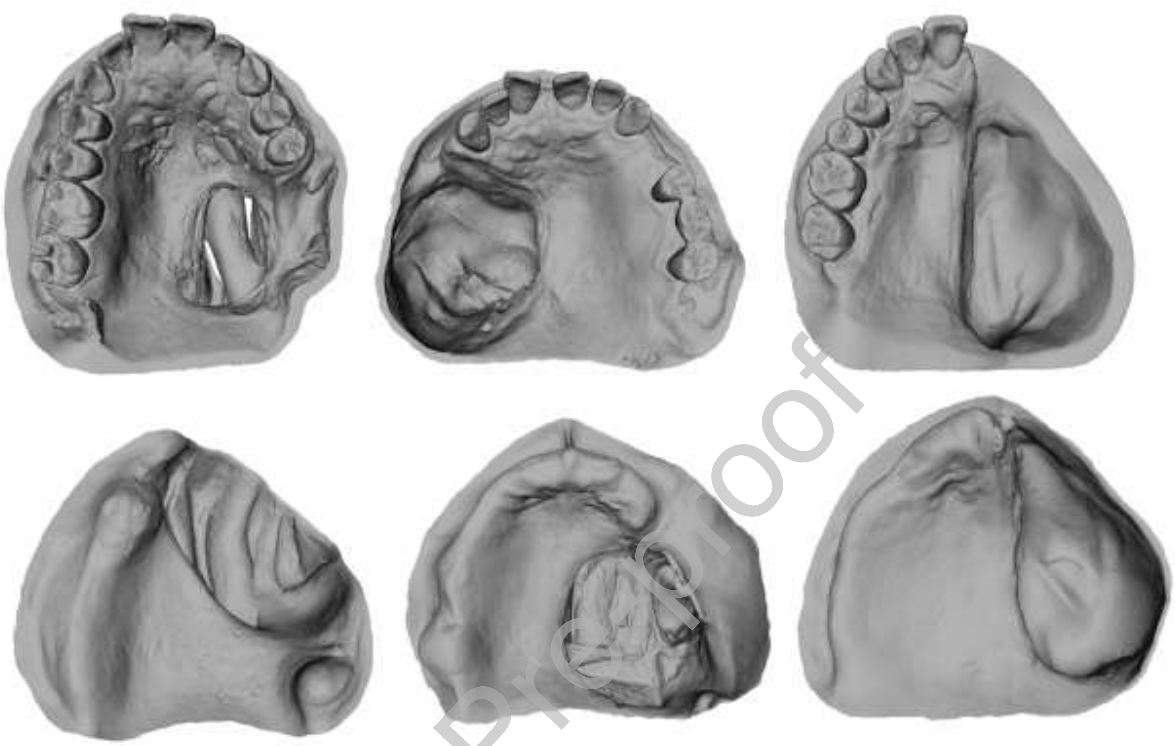

Figure 1. The standard tessellation language (STL) file of patient-based dentate and edentulous maxillectomy defect models acquired with the intraoral scanner.

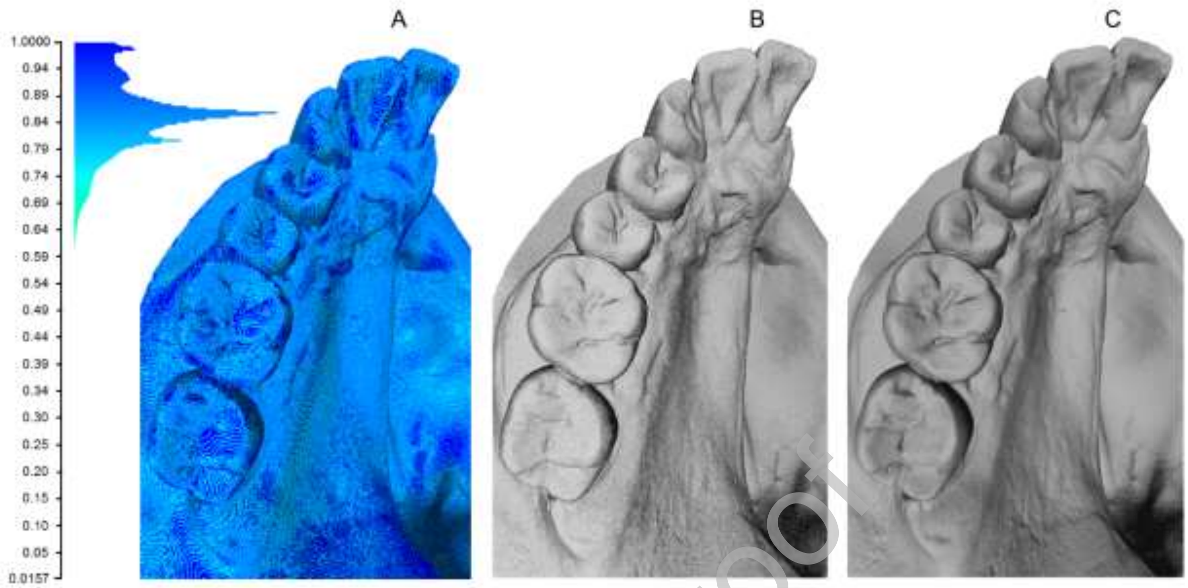

Figure 2a: A zero triangular mesh reduction (R_0) for dentate maxillectomy defect model. A. The triangle quality depending on shape and aspect ratio view with histogram; B. Wireframe view; C. View of the polygon surfaces.

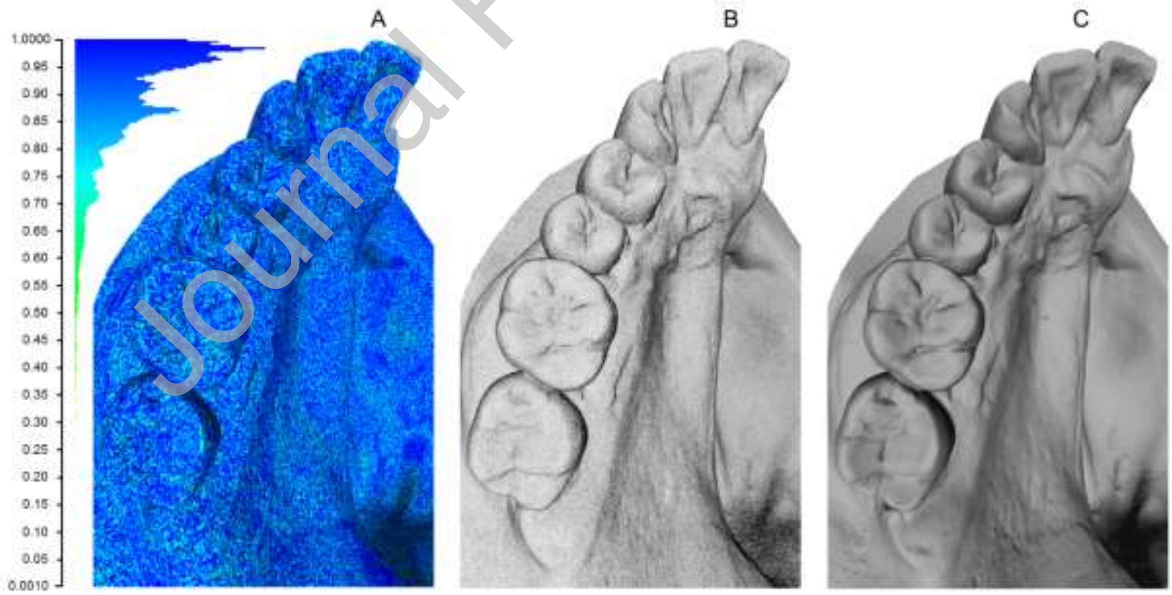

Figure 2b: A fifty percent (50%) triangular mesh reduction (R_1) for dentate maxillectomy defect model. A. The triangle quality depending on shape and aspect ratio view with histogram; B. Wireframe view; C. View of the polygon surfaces.

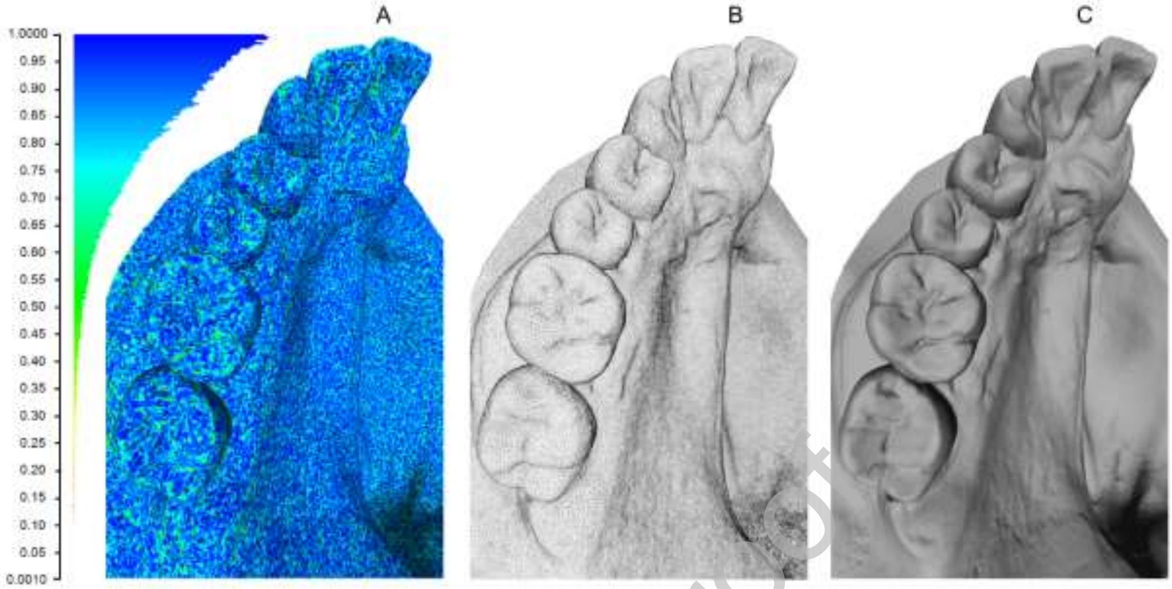

Figure 2c: A seventy five percent (75%) triangular mesh reduction (R_2) for dentate maxillectomy defect model. A. The triangle quality depending on shape and aspect ratio view with histogram; B. Wireframe view; C. View of the polygon surfaces.

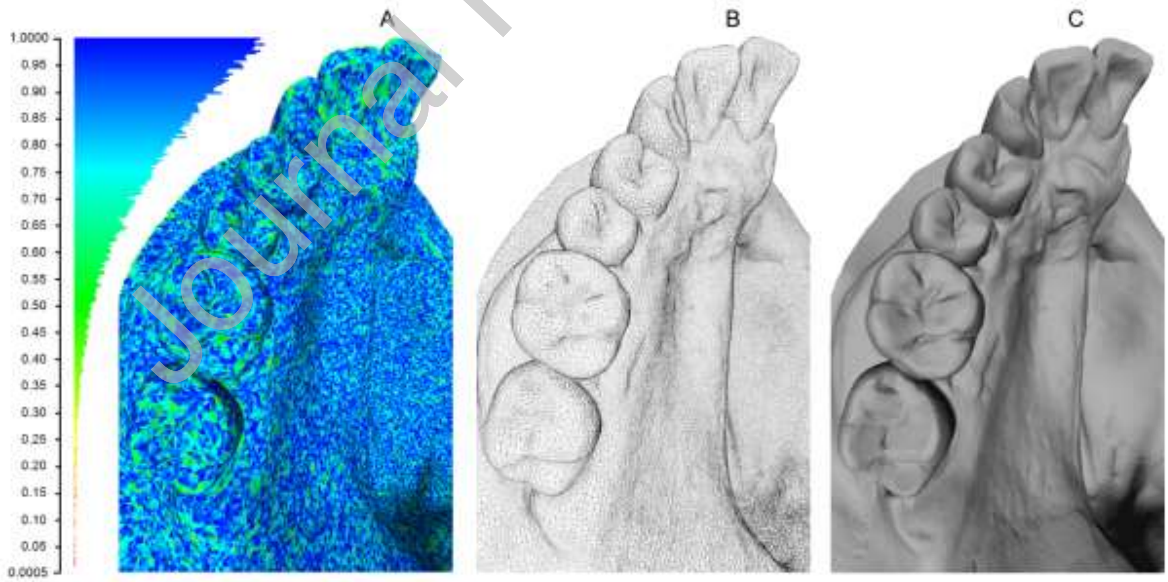

Figure 2d. A ninety percent (90%) triangular mesh reduction (R_3) for dentate maxillectomy defect model. A. The triangle quality depending on shape and aspect ratio view with histogram; B. Wireframe view; C. View of the polygon surfaces.

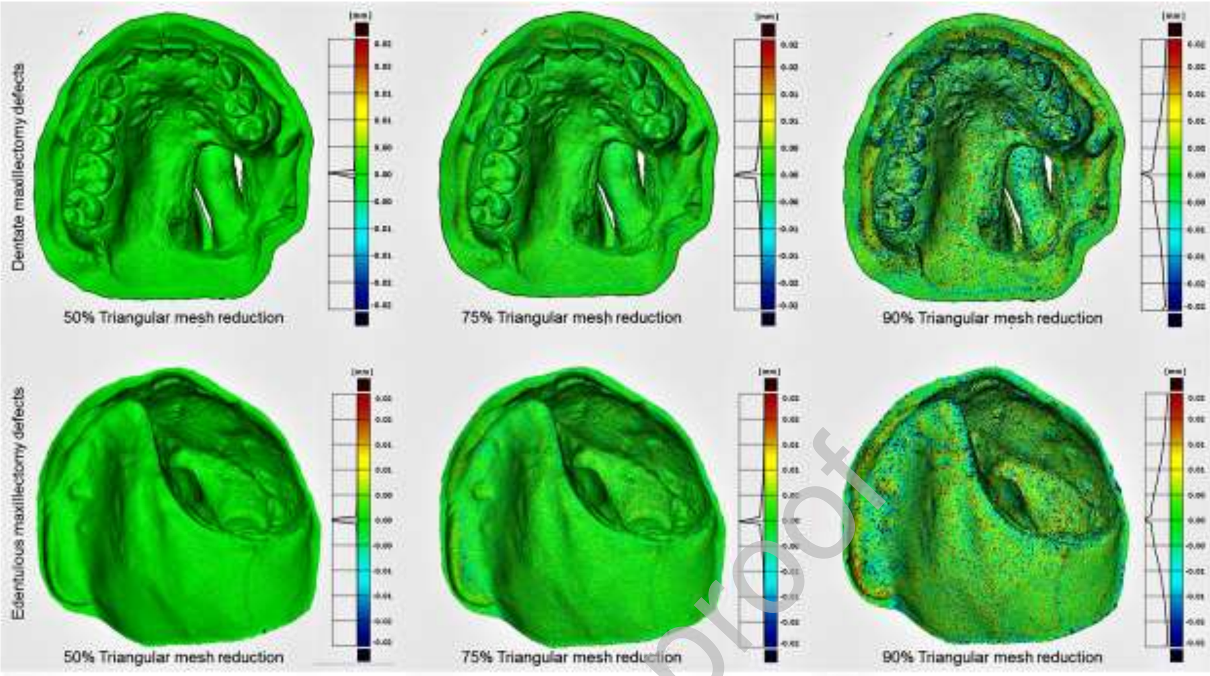

Figure 3. Details of the colorimetric map generated in the 3D evaluation software for geometrical trueness evaluation and compression of the reference data to test data.

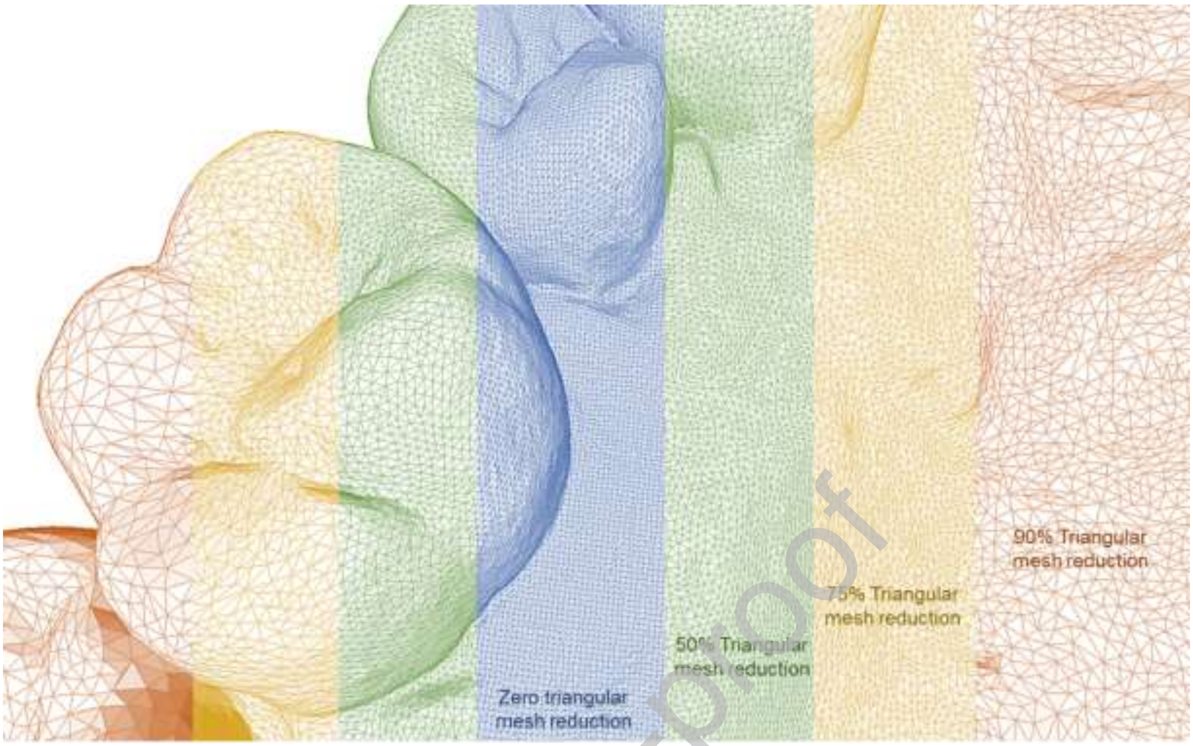

Figure 4: Wireframes showing the density of triangles within various triangular mesh reduction percentages of multi-angled dentate surfaces and flatter surfaces. Zero reduction R_0 (Blue), 50% triangular mesh reduction R_1 (Green), 75% triangular mesh reduction R_2 (Yellow), and 90% triangular mesh reduction R_3 (Orange).