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RESEARCH AND EDUCATION

Percentage of mesh reduction appropriate for designing digital obturator prostheses on personal computers

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ABSTRACT

Statement of problem. Computer-aided design (CAD) of maxillofacial prostheses is a hardware-intensive process. The greater the mesh detail is, the more processing power is required from the computer. A reduction in mesh quality has been shown to reduce workload on computers, yet no reference value of reduction is present for intraoral prostheses that can be applied during the design.

Purpose. The purpose of this simulation study was to establish a reference percentage value that can be used to effectively reduce the size and polygons of the 3D mesh without drastically affecting the dimensions of the prosthesis itself.

Material and methods. Fifteen different maxillary palatal defects were simulated on a dental cast and scanned to create 3D casts. Digital bulbs were fabricated from the casts. Conventional bulbs for the defects were fabricated, scanned, and compared with the digital bulb to serve as a control. The polygon parameters of digital bulbs were then reduced by different percentages (75%, 50%, 25%, 10%, 5%, and 1% of the original mesh) which created a total of 105 meshes across 7 mesh groups. The reduced mesh files were compared individually with the original design in an open-source point cloud comparison software program. The parameters of comparison used in this study were Hausdorff distance (HD), Dice similarity coefficient (DSC), and volume.

Results. The reduction in file size was directly proportional to the amount of mesh reduction. There were minute yet insignificant differences in volume ($P>.05$) across all mesh groups, with significant differences ($P<.001$) in HD. The differences were, however, only found with DB1. DSC showed a progressive dissimilarity until DB25 (0.17%), after which the increase was more prominent (0.46% to 4.02%).

Conclusions. A reduction of up to 75% polygons (25% of the original mesh) was effectively carried out on simulated casts without substantially affecting the amount of similarity in volume and geometry. (J Prosthet Dent 2020;■:■-■)

Digital designs rely on computer-aided design (CAD) to produce and process virtual 3D polygon casts. The cast is known as a 3D mesh, and the quality of detail is dependent on the polygon parameters: vertices, triangles, edges, and points which make up the mesh. In plain terms, the greater the detail, volume, and texture quality, the more polygons are present within the 3D mesh.[1] An increased number of triangles, in turn, demands higher computing power. An increase in polygons also affects the overall file size of the 3D cast, and thus it occupies more storage space in a computer drive.[2]

The surfaces of any prosthesis of the maxillofacial region require accurate reproduction of volume and geometric details, for both esthetics and fit.[3,4] When using low-specification hardware such as a personal laptop for designing these prostheses in full detail, the resource-intensive processes slow down the device. There are issues of lagging, software crashing, and increased processing time for each command.[2] This results in it taking longer to complete the overall design.

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Clinical Implications

A reduction in 3D mesh polygons of up to 75% can be carried out to facilitate computer-aided design of obturator prostheses on personal computers.

It can also lead to frustrations for the operator should any errors occur which require redesigning a step.

The issue can be overcome by using powerful expensive hardware. To make digital designs readily available, the operator should be able to design the prosthesis with a readily available computer. One way of making the workflow less resource-intensive would be to reduce the vertices and triangles within the design. This would effectively reduce stress on the hardware and allow for faster processing time albeit with a reduction in mesh quality and loss of detail.[5] Large reductions in mesh quality, however, may clinically lead to lack of prosthesis retention and poor fit while negatively affecting the volumetric and geometric properties of the prosthesis.

This in vitro study evaluated the percentage reduction that can be made to a CAD-based 3D maxillofacial obturator prosthesis mesh without significantly affecting the volume or degree of similarity when compared with the same prosthesis made by conventional methods. This can help clinicians establish a reference value for mesh reduction while carrying out CAD of maxillofacial prostheses. The null hypothesis was that there will be no significant volumetric or geometric differences in digital bulbs after mesh reduction.

Figure 1. A, Simulation of defects on dental casts. B, Fabrication of conventional bulb.

MATERIAL AND METHODS

Fifteen maxillary dentulous casts were fabricated, and palatal defects were simulated to model different palatal defects after maxillectomy (Fig. 1A). The casts were scanned by using a laser scanner (3D scanner ultra; NextEngine Inc) to obtain 3D casts of the defect site on which the digital obturator would be designed. The same casts were subsequently used to make the conventional prostheses (Fig. 1B).

Following the methodology of previous studies,[6,7] the digital obturator was made on a laptop with 8 GB of RAM (Ryzen 5; AMD) using CAD software (Meshmixer; Autodesk Inc). The Select function was used to isolate the defect site followed by the Reverse Fill function to create the bulb. The Inspector tool served to close the bulb lid as well as fix any holes. This was then followed by the Make Solid function and subsequent Sculpt function to contour the mesh. The final obturator design was then exported to standard tessellation language (STL) file format and renamed "DB100" because the mesh polygons were not reduced and it retained 100% of its mesh details. The polygon parameters vertices, triangle count, and total size of the STL file were recorded.

The DB100 file was selected in Meshmixer, and the Reduce function was applied, preserving the shape and boundaries (Fig. 2). The first parameter of reduction was set to 25%. Thus, the final reduced mesh was 75% of DB100. The polygon parameters were recorded, and the final mesh was exported in STL and renamed "DB75". DB100 was used again following the same workflow of reduction to obtain meshes of 50%, 25%, 10%, 5%, and 1% of DB100. The polygon parameters were recorded for all instances, and the files were exported and saved individually as DB50, DB25, DB10, DB5, and DB1. They, along with DB75, were collectively called "DB meshes". Thus, a total of 105 files were generated from the 15 defect models.

The conventional obturator bulbs for the simulated defects were made by packing autopolymerizing polymethyl methacrylate (PMMA) (Probase; Ivoclar Vivadent AG) onto the defect of the cast. The polymerized acrylic resin obturators were scanned by using the same desktop scanner. The scanned bulbs were saved as STL files and renamed "CB" (conventional bulb).

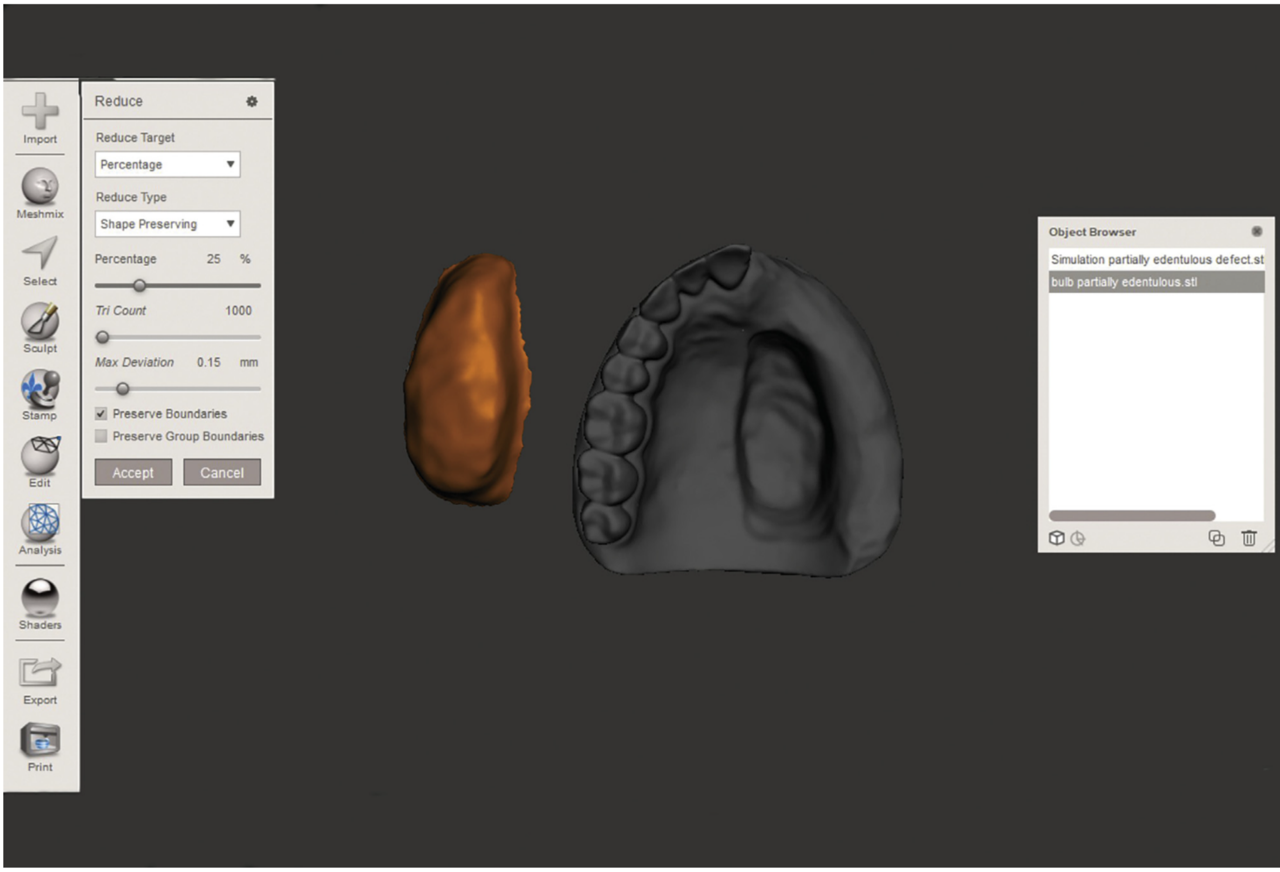

Figure 2. Polygon reduction of digitally designed bulb by using open-source CAD software program. CAD, computer-aided design.

The comparison between CB and DB100 was done following the study by Egger et al[8] in which the authors compared the geometric interpoint mismatches between 2 solids using the Hausdorff distance (HD), while comparing the volumetric spatial overlap between similar objects by using virtual volume and Dice similarity coefficient (DSC). The authors used these methods to effectively compare manual and software-based computed tomography volume registration in a study of glioblastoma multiforme. The same methods of comparison were later used to accurately evaluate and compare craniofacial morphology[9] and to assess design similarities of maxillofacial prostheses[7] by using an open-source point cloud comparison tool (CloudCompare; DanielGM). Thus, the same workflow was adapted into the present study where CB were loaded into the software to act as the reference in volumetric and geometric comparison of the digital bulbs.

The volume (in cubic units) of CB and DB100 was recorded by using the Measure Volume function under the Mesh menu. The Move Bounding-Box function was used to overlap the conventional bulb with the DB, and the Fine Registration (ICP) function was used to align the 2 meshes, holding the conventional bulb as a reference and root mean square (RMS) difference to 1.0e-5 with a 100% final overlap set. The 2 meshes were then selected, and the Cloud-Mesh Distance function was applied to determine the HD. The aligned meshes were processed through the Cork plug-in, and the Intersection function was applied to obtain a singular mesh of the intersect. The volume of the intersect was measured, followed by the DSC measured using the formula:

$2(CB \cap DB100)/(CB + DB100)$, where $\cap$ is the intersection, CB is the conventional bulb, and DB is the digital bulb.

To compare among DB meshes, the same method was carried out, keeping DB100 as reference and comparing the DSC and HD of the DB meshes individually. The process was repeated for all 105 files generated from 15 models. A statistical software program (IBM SPSS Statistics, v24.0; IBM Corp) was used to analyze the data. Normal distributions were analyzed by using Kolmogorov-Smirnov test. Volumetric analyses were carried out by using Kruskal-Wallis 1-way test. HD were analyzed using 1-way ANOVA (α=.05).

RESULTS

The number of vertices at any given percentage reduction of DB was approximately half that of the triangles present

Table 1. Mean ±standard deviation percentage reduction (%) of 3D mesh and associated polygon parameters

Group	Mesh %	No. of Vertices Present in the Mesh	No. of Triangles Present in the Mesh	STL File Size (kb)	% Reduction in File Size
DB100	100	9600.07 ±2494.24	19129.47 ±4917.28	937.93 ±243.67	0
DB75	75	7200.00 ±1870.79	14396.00 ±3741.57	703.47 ±182.60	24.99
DB50	50	4800.73 ±1247.13	9597.47 ±2494.26	469.20 ±121.78	49.98
DB25	25	2401.20 ±623.57	4793.60 ±1249.01	234.87 ±60.96	74.95
DB10	10	961.33 ±249.45	1918.67 ±498.90	94.20 ±24.33	89.95
DB5	5	492.80 ±149.68	958.93 ±249.69	47.40 ±12.21	94.95
DB1	1	97.47 ±24.92	190.93 ±49.83	11.00 ±5.95	98.83

Table 2. Comparison of mean ±standard deviation volume, Hausdorff distance (HD), Dice similarity coefficient (DSC) between conventional obturator (CB) and digitally designed obturator at full detail (DB100), and overall percentage similarity

Group	Volume (mm^3)	HD (mm)[a]	DSC	Percentage similarity[b]
CB	3844.12 ±1712.06	0.3310 ±0.1736	0.8732 ±0.0456	87.32%
DB100	3373.93 ±1559.62			

[a]HD obtained from software-based cloud point comparison of approximately 50 000 points. [b]% Similarity obtained by multiplying DSC by 100.

Table 3. Mean ±standard deviation volumetric comparisons at different levels of mesh reduction

Group	Mean Volume (mm^3)	Comparison Against CB[b]	Median (IQR)	χ^2 (df)	P[a,c]
DB100	3373.94 ±1559.62	12.23% less	2821.32 (2575.27)	1.365 (6)	.968
DB75	3373.54 ±1559.44	12.24% less	2820.97 (2575.00)		
DB50	3372.84 ±1559.29	12.26% less	2820.41 (2574.62)		
DB25	3370.06 ±1558.70	12.33% less	2818.12 (2573.34)		
DB10	3360.09 ±1556.32	12.59% less	2808.66 (2567.37)		
DB5	3342.38 ±1551.59	13.05% less	2793.03 (2555.80)		
DB1	3185.28 ±1513.09	17.14% less	2666.05 (2475.87)		

df, degrees of freedom; IQR, interquartile range. [a]Significant at $P<.05$. [b]% volume comparison against mean volume of CB (3844.12 mm^3). [c]Kruskal-Wallis 1-way test: parametric assumptions not met. Kolmogorov-Smirnov test significant ($P<.05$).

Table 4. Mean ±standard deviation Hausdorff distance comparison (against DB100)

Group	Mean HD (mm)	F-stat	P[a,b,c]
DB100	0.000000	–	–
DB75	0.000046 ±0.000029	43.917	<.001
DB50	0.000118 ±0.000064		
DB25	0.000148 ±0.000140		
DB10	0.001235 ±0.000605		
DB5	0.004364 ±0.001767		
DB1	0.023635 ±0.013326		

[a]Significant at $P<.05$. [b]One-way ANOVA: all parametric assumptions met. Kolmogorov-Smirnov test not significant ($P>.05$). Data normally distributed. [c]Post hoc analysis (Tukey test): DB100 against DB75 not significant ($P>.999$), DB100 against DB50 not significant ($P>.999$), DB100 against DB25 not significant ($P>.999$), DB100 against DB10 not significant ($P=.994$), DB100 against DB5 not significant ($P=.232$), DB100 against DB1 significant ($P<.001$).

Table 5. Mean ±standard deviation Dice similarity coefficient and percentage similarity comparisons (against DB100)

Group	Mean DSC	Average % Similarity[a]	% Dissimilarity Against DB100[b]
DB100	1.000000	100	0
DB75	0.999816 ±0.000041	99.98	0.02 more
DB50	0.999445 ±0.000139	99.94	0.06 more
DB25	0.998255 ±0.000590	99.83	0.17 more
DB10	0.995376 ±0.001113	99.54	0.46 more
DB5	0.990871 ±0.002246	99.08	0.92 more
DB1	0.959792 ±0.012641	95.98	4.02 more

[a]Average % similarity=mean DSC×100. [b]% dissimilarity against DB100=100–average % similarity.

in the mesh. The file size measured in kilobytes showed an almost uniform reduction in size. Detailed results are presented in Table 1. The volume of DB100 was approximately 12.2% less than that of CB, with a percentage similarity of 87.3% (Table 2).

When DB meshes were compared against DB100, there were small but statistically insignificant ($P>.05$) reductions in volume at every level of mesh reduction (Table 3). However, statistical evaluation of HD revealed significant differences ($P<.001$) among the mesh groups. Post hoc analysis revealed negligible differences when DB100 was compared with DB75, DB50, and DB25 ($P>.999$). Significant changes were only observed with DB1 ($P<.001$). Details of the findings are presented in Table 4.

DSC evaluation showed that a slowly rising dissimilarity of 0.02% to 0.17% was present among DB75, DB50, and DB25 when compared with DB100. However, that percentage increased exponentially to a dissimilarity of 0.46% to 4.02% when the comparisons were made against DB10, DB5, and DB1 (Table 5).

Although not obvious at first glance virtually (Fig. 3A), wireframe visualization demonstrates the decrease in the number of triangles making up the prosthesis at every level of mesh reduction (Fig. 3B). The decreased number of triangles would translate into progressively sharper contour margins which can be observed when the bulbs are 3D printed (Fig. 3C).

DISCUSSION

The objective of this study was to evaluate the percentage mesh reduction appropriate for CAD on lower-end

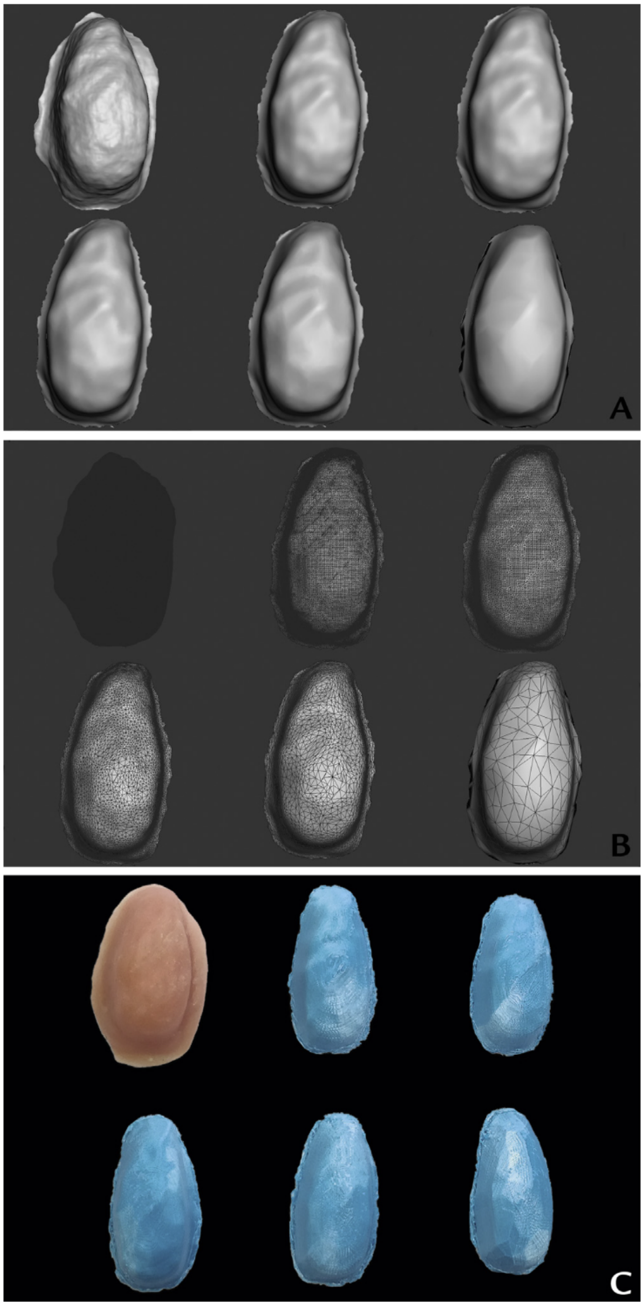

Figure 3. A, Comparison of virtual obturator bulbs at different percentage mesh reduction. From top left: CB, DB100, DB75, DB25, DB10, DB1. B, Comparison of polygon density and triangle count of obturator bulbs at different percentage mesh reduction. From top left: CB, DB100, DB75, DB25, DB10, DB1. C, Comparison of physical 3D printed obturator bulbs at different percentage mesh reduction. From top left: CB, DB100, DB75, DB25, DB10, DB1.

computers without substantially affecting the volume or similarities. The findings suggested no significant differences in volume but significant differences in HD; therefore, the null hypothesis was only partially rejected.

The first noticeable change was that a reduction in vertices and triangle polygons reduced the overall size of the STL file. This could solve storage space issues for practitioners storing and working with large number of obturators on their computers.

Second, DB100 had lower virtual volumes (12% less) than CB, mainly because of the differences when designing the extension of the conventional obturator periphery and scanning-related discrepancies. Regardless, a further loss in volume with an existing discrepancy could clinically result in a poor fit of the prosthesis and fluid leakage in the patient's mouth. As Farook et al[7] suggested, the amount of mesh reduction directly affects the ease of CAD operations on low-end computers; however, it negatively affects the amount of volumetric and mesh detail. In the present study, volume, HD, and DSC all suggest that mesh reductions up to DB25 produced statistically and geometrically minute and insignificant differences while any reduction beyond that group exponentially increased the differences in parameters to a point of significance. Therefore, a fine balance was found up to 75% mesh reduction.

HD allows for precise measurements of interpoint mismatches between mutual points of similar objects. Sharma et al[10] suggested that mismatch or errors of up to 0.50 mm is generally considered acceptable in any given instance, although some authors argue that value to be 5 mm and suggest that it is largely dependent on the type of practice in which the measurements are in use.[7] DSC estimates the amount of spatial overlap in volume between 2 similar objects to evaluate the amount of similar space between them; the acceptability threshold is generally set at 0.70.[11] The present study met both acceptability thresholds, suggesting that although digital bulbs are not perfect, they are geometrically and statistically quite similar to their conventional counterparts. Further favoring digital workflows, Lo Russo et al[12] reported that regardless of the methods used, digitally designed prostheses will have some amount of volumetric and geometric difference to conventionally made prostheses which can be considered acceptable.

Compared with larger extraoral maxillofacial prostheses or cranial plates, small reductions in mesh detail are often not significant in intraoral prostheses until substantial polygon reduction has been made (Fig. 3B). This is because when few polygons make up each segment of the prosthesis, there is a loss of detail in areas which were previously represented by more polygons. This ultimately creates multiple acute angles during the manufacturing phase, as seen in DB1 but not in DB25 (Fig. 3C). This follows the same principles as how low resolutions in larger images tend to pixelate and become less detailed.[13] Thus, mesh reduction in larger extraoral prostheses might yield different point cloud comparison values, and therefore, future studies are recommended to explore the subject. Furthermore, the decimation algorithm for mesh reduction is present in many CAD software packages, and future studies could be conducted to explore and compare their accuracy in the process of mesh reduction in prosthodontics. Limitations of the present study include the nonclinical environment, and intraoral fit and accuracy were not evaluated; therefore, these should also be a topic of future research.

CONCLUSIONS

Based on the findings of this simulation study, the following conclusion was drawn:

1. Mesh reduction of up to 75% can be applied when designing intraoral maxillofacial prostheses, to reduce computational power requirements without significantly affecting the volumetric or geometric properties of the obturators.

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