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RESEARCH AND EDUCATION

A virtual analysis of the precision and accuracy of 3-dimensional ear casts generated from smartphone camera images

Taseef Hasan Farook, MScDent,[a] Farah Rashid, BDS,[a] Nafij Bin Jamayet, MScDent,[b,c] Johari Yap Abdullah, PhD,[d] James Dudley, DClinDent,[e] and Mohammad Khursheed Alam, PhD[f]

ABSTRACT

Statement of problem. The anatomic complexity of the ear challenges conventional maxillofacial prosthetic rehabilitation. The introduction of specialized scanning hardware integrated into computer-aided design and computer-aided manufacturing (CAD-CAM) workflows has mitigated these challenges. Currently, the scanning hardware required for digital data acquisition is expensive and not readily available for prosthodontists in developing regions.

Purpose. The purpose of this virtual analysis study was to compare the accuracy and precision of 3-dimensional (3D) ear models generated by scanning gypsum casts with a smartphone camera and a desktop laser scanner.

Material and methods. Six ear casts were fabricated from green dental gypsum and scanned with a laser scanner. The resultant 3D models were exported as standard tessellation language (STL) files. A stereophotogrammetry system was fabricated by using a motorized turntable and an automated microcontroller photograph capturing interface. A total of 48 images were captured from 2 angles on the arc (20 degrees and 40 degrees from the base of the turntable) with an image overlap of 15 degrees, controlled by a stepper motor. Ear 1 was placed on the turntable and captured 5 times with smartphone 1 and tested for precision. Then, ears 1 to 6 were scanned once with a laser scanner and with smartphones 1 and 2. The images were converted into 3D casts and compared for accuracy against their laser scanned counterparts for surface area, volume, interpoint mismatches, and spatial overlap. Acceptability thresholds were set at <0.5 mm for interpoint mismatches and >0.70 for spatial overlap.

Results. The test for smartphone precision in comparison with that of the laser scanner showed a difference in surface area of 774.22 ±295.27 mm^2 (6.9% less area) and in volume of 4228.60 ±2276.89 mm^3 (13.4% more volume). Both acceptability thresholds were also met. The test for accuracy among smartphones 1, 2, and the laser scanner showed no statistically significant differences (*P*>.05) in all 4 parameters among the groups while also meeting both acceptability thresholds.

Conclusions. Smartphone cameras used to capture 48 overlapping gypsum cast ear images in a controlled environment generated 3D models parametrically similar to those produced by standard laser scanners. (J Prosthet Dent 2021;■:■-■)

For a maxillofacial prosthodontist, ear rehabilitation is a challenging endeavor primarily because of difficulties in reconstructing the anatomic structure by conventional means.[1] A practical development has been scanning the healthy ear and mirroring the image by using computer-aided design (CAD) technology followed by 3-dimensional (3D) printing of the ear.[1-3] However, scanning technologies for this purpose of data acquisition remain expensive and may prevent prosthodontists in developing regions from adopting digital maxillofacial prosthetics.

In the last decade, smartphones have contributed substantially to medicine[4] while stereophotogrammetry (the creation of 3D models using multiple overlapping images) has seen increased use in different aspects of dentistry.[5-7]

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[a]Research Fellow, Maxillofacial Prosthetic Service, Prosthodontic Unit, School of Dental Sciences, Health Campus, Universiti Sains Malaysia, Kubang Kerian, Kota Bharu, Kelantan, Malaysia.
[b]Ex-Senior lecturer, School of Dental Sciences, Health Campus, Universiti Sains Malaysia, Kubang Kerian, Kota Bharu, Kelantan, Malaysia.
[c]Senior Lecturer, Division of Clinical Dentistry (Prosthodontics), School of Dentistry, International Medical University, Kuala Lumpur, Malaysia.
[d]Senior lecturer, Craniofacial Imaging and Additive Manufacturing Laboratory, School of Dental Sciences, Health Campus, Universiti Sains Malaysia, Kubang Kerian, Kota Bharu, Kelantan, Malaysia.
[e]Associate Professor, Adelaide Dental School, The University of Adelaide, South Australia, Australia.
[f]Associate Professor, College of Dentistry, Jouf University, Sakaka, Saudi Arabia.

Clinical Implications

In a controlled environment, smartphone cameras can generate accurate 3D models for a CAD-CAM workflow for maxillofacial prostheses.

However, whether smartphone images are sufficiently accurate to reconstruct a complex organ such as the ear is unclear. If favorable, such findings could facilitate low-cost, readily available digital data acquisition which can benefit maxillofacial prosthodontists providing extraoral prostheses.

Previous studies[1,8-11] have evaluated parameters including surface area, volume, interpoint mismatches, and spatial overlap to compare the accuracy of 3D casts virtually. Stereophotogrammetry has been used successfully to scan dental casts by using professional cameras to make pictures of the cast at 15-degree intervals under adequate lighting conditions.[5] However, a study investigating the use of smartphones in non-standardized conditions for facial defect 3D modeling reported on the lack of accuracy of smartphone cameras.[12]

The aim of the present study was to virtually compare the accuracy and precision of 3D-ear casts generated by scanning gypsum casts with smartphone cameras and a desktop laser scanner. The null hypothesis was that no significant differences would be found in the virtual parameters when comparing the accuracy of a smartphone camera with that of a desktop laser scanner in scanning ear casts.

MATERIAL AND METHODS

In previous studies using a similar methodology, the effect size required to observe significant changes of accuracy and precision was reported as being very large (>1.00).[12,13] The current study was performed with an effect size of 1.00, α=.05 and power of 0.80, which indicated a total sample size of 15. An additional 15% of samples were included based on predicted computer and human errors. Therefore, a total sample size of 18 was distributed evenly across 3 groups.

Six ear models were fabricated in green stone (Pro-Solid Super; Saint-Gobain Formula GmbH from a single preexisting silicone mold). The ear casts were scanned with a laser scanner (3D Scanner Ultra HD; NextEngine Santa Monica) set on the default macrosettings. The scanned 3D models were meshed and exported as standard tessellation language (STL) files by using a CAD software program (Geomagic Design X; 3D systems).

Smartphone 1 (Oneplus-5t; BBK Electronics) was selected for the next phase. A motorized turntable was designed with a microcontroller system (Arduino UNO; Arduino systems) to revolve in 15-degree steps.[5] The turntable was connected to a Bluetooth module (HM-10; Destiny Electronic), which, in turn, commanded the smartphone to capture a photo at 15-degree intervals. The software codes used for the process are provided in Supplemental Table 1, available online.

The backs of the ear casts were marked in pencil and then placed upright on the turntable. The smartphone was attached on a custom metallic arc which ensured a 20-cm distance between the turntable and the smartphone at any given point. The fixtures were placed at 20 degrees and 40 degrees above the base of the turntable.

The smartphone was fixed at each fixture and programmed by the Arduino processor to automatically make 24 images of the ear as it revolved. This was repeated at both fixtures, which resulted in 48 images of each ear model.

As success with stereophotogrammetry depends on proper lighting,[5] 12-V light-emitting diode (LED) white lights strips (5050 White 6000K; Shopee Malaysia) surrounded and illuminated the turntable and ear to an average of 1250 lux. The room was kept dark to prevent interference from ambient light. A matte black sheet (Extra Black; Campap Arto) was placed on the background to absorb any reflective light and ensure that the smartphone camera focused on the ear cast.

The images were then exported to an image-to-3D software program (ReCap Photo; Autodesk Inc) where the 3D cast of the ear was constructed. Digital calipers (Model CD-6; Mitutoyo) were used to measure the pencil markings on the physical ear casts, and the values were transferred to the software program to scale to actual size.[12] The ear casts were then processed by using a CAD software program (Meshmixer; Autodesk Inc) and exported as an STL file. Both the laser scanned and smartphone-generated ear casts were then virtually compared. The entire workflow is summarized in Figure 1.

To test for precision and repeatability, ear cast 1 was captured 5 times with smartphone 1. The 5 scans were analyzed virtually for mesh surface area (MSA), virtual volume (VV), interpoint mismatch by the Hausdorff distance, and spatial overlap by the Dice similarity coefficient. The analyses were done by using an open-source CAD software program (Meshlab; Consiglio Nazionale delle Ricerche) and a point cloud comparison software program (Cloudcompare; https://www.danielgm.net/cc/) as in previous studies.[1,10] Interpoint mismatches and spatial overlap were analyzed by using the laser-scanned counterparts as the reference. The acceptability threshold was set at <0.50 mm for interpoint mismatches[14] and >0.70 for spatial overlap.[15]

To test for accuracy, smartphone 2 (iPhone 6s; Apple Inc) was introduced to the standardized arrangement to evaluate whether results were still unfavorable, as reported in previous research.[12] All 6 ear casts were

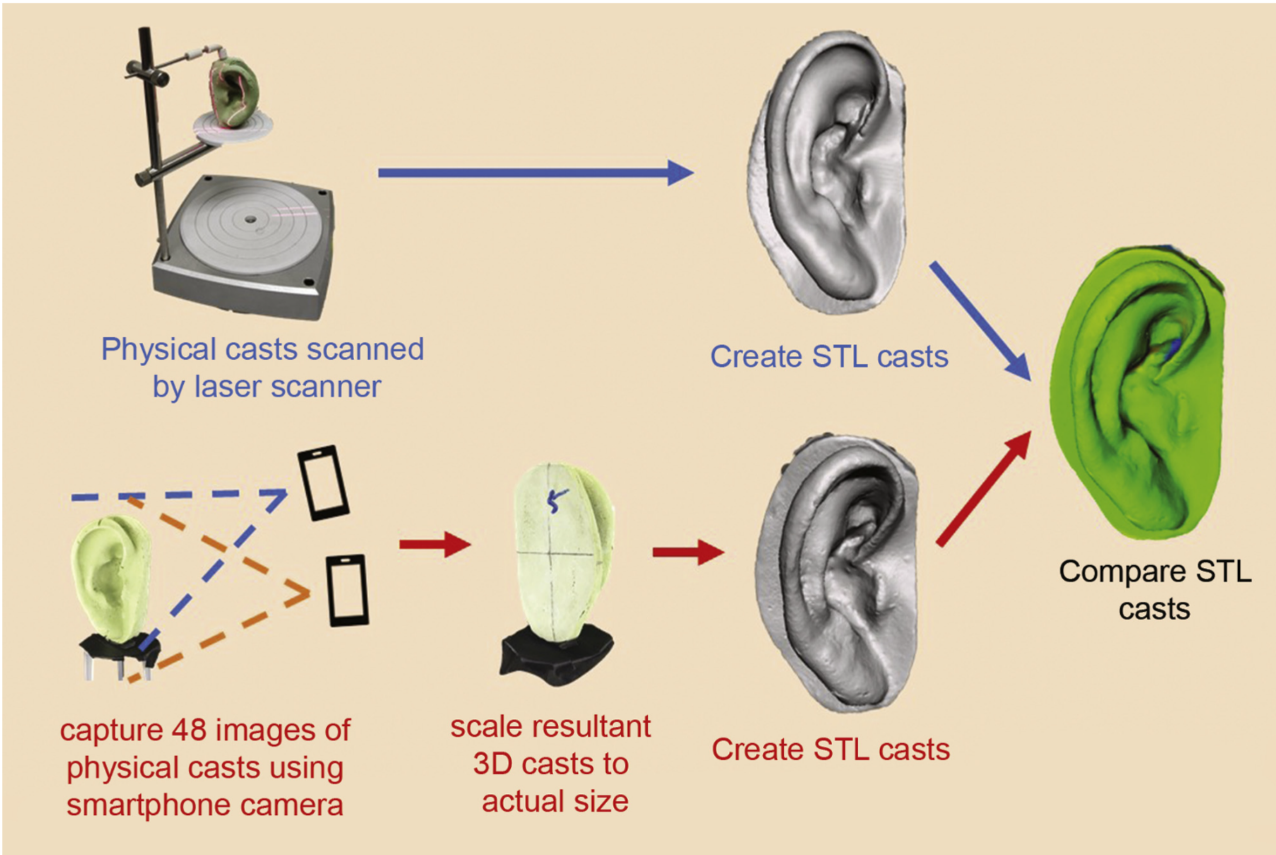

Figure 1. Summary of workflow carried out. STL, standard tessellation language.

captured once by using both smartphones with 48 images per cast and processed using image-to-3D software program (Recap photo; AutoDesk Inc). The resultant STL files were compared with their laser scanned counterparts for MSA, VV, interpoint mismatches, and spatial overlap.

Statistical analyses were carried out by using a statistical software program (IBM SPSS Statistics, v24.0; IBM Corp). All 4 virtual parameters were tested for normality by using the Kolmogorov-Smirnov and Shapiro-Wilk tests. MSA and VV were analyzed by using 1-way ANOVA. Interpoint mismatches and spatial overlap were analyzed by selecting the laser scanned casts as reference. The results of smartphones 1 and 2 were then compared by using an independent sample *t* test (α=.05).

RESULTS

When testing for precision, a mean surface area of 10 407.17 ±295.28 mm^2 was recorded from 5 successive measurements of ear 1 for smartphone 1 compared with 11 181.39 mm^2 for the standard laser scanner (93.1% of laser scanned surface area). Smartphone 1 also produced a mean volume of 35 748.94 ±2276.89 mm^3 (13.4% more volume) compared with 31 520.34 mm^3 for the laser scanner. When interpoint mismatches between the laser scanner and smartphone 1 were considered, a mean mismatch of 0.33 ±0.16 mm was observed, which satisfied the <0.50 mm acceptability threshold. The distribution of the mismatches is shown in Figure 2 as color maps. Most of the mesh triangles were found at approximate distance=0 mm, which is considered ideal; however, there were mismatches of <4 mm within the inner folds of the ear (concha, antihelix, and incisura). Furthermore, spatial overlap analysis showed similarities within the range of 0.85 to 0.92, which also satisfied the >0.70 acceptability threshold. Thus, 5 successive 48-image scans demonstrated similar geometric properties while satisfying both acceptability thresholds. The data obtained during precision testing are provided in Supplemental Table 2, available online.

The accuracy results for the laser scanner, smartphone 1, and smartphone 2 are presented in Table 1. No significant differences among the 4 virtual parameters (MSA, *P*=.05; VV, *P*=.45; interpoint mismatches, *P*=.76; and spatial overlap. *P*=.30). Furthermore, both the interpoint mismatch acceptability threshold (<0.50 mm) and spatial overlap acceptability threshold (>0.70) were met for all 6 scanned ear casts. The distribution of mismatches for both smartphone 1 (Fig. 2B) and smartphone

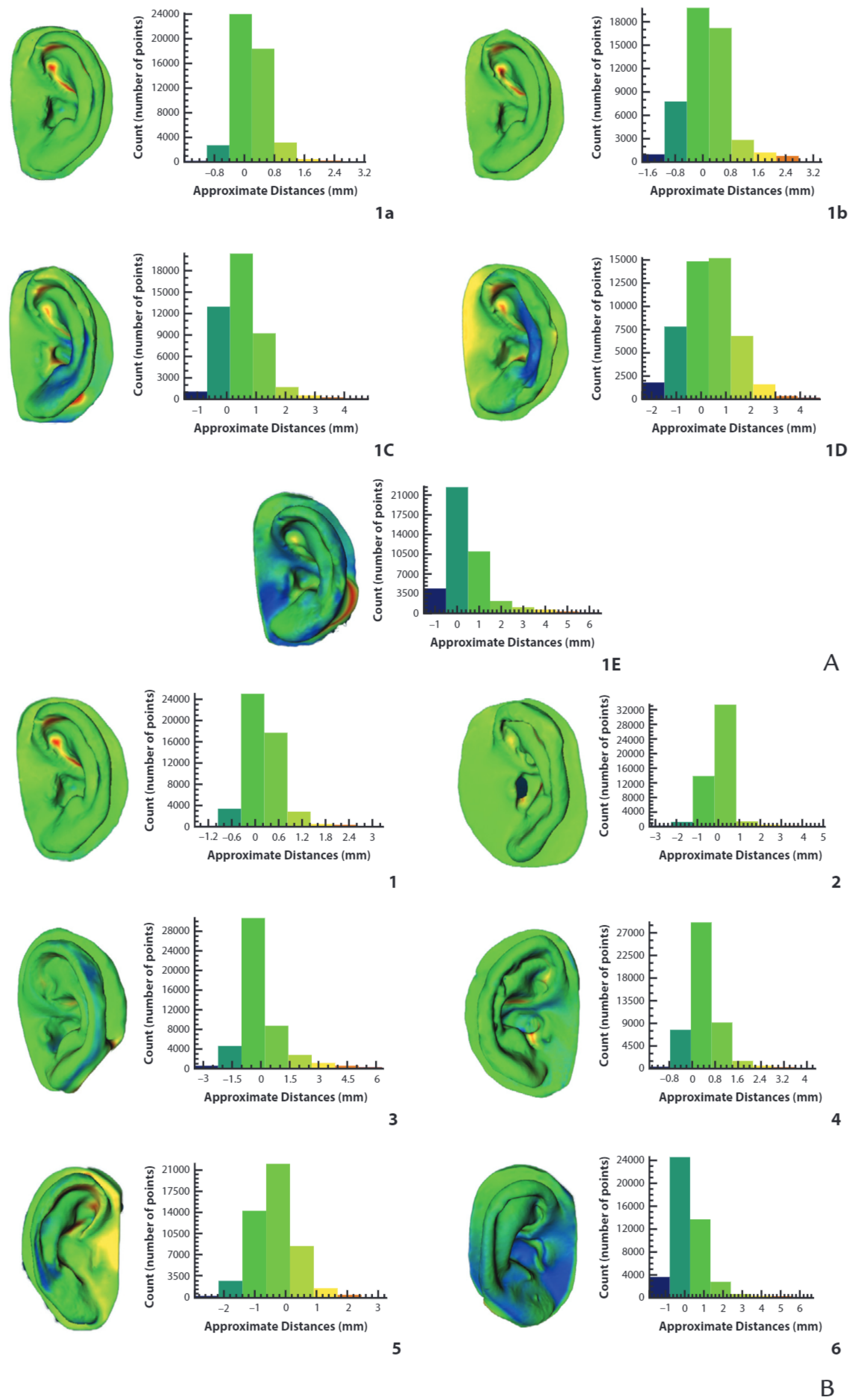

Figure 2. Color map of distribution of interpoint mismatches. A, In test for precision. B, In test for accuracy with smartphone 1.

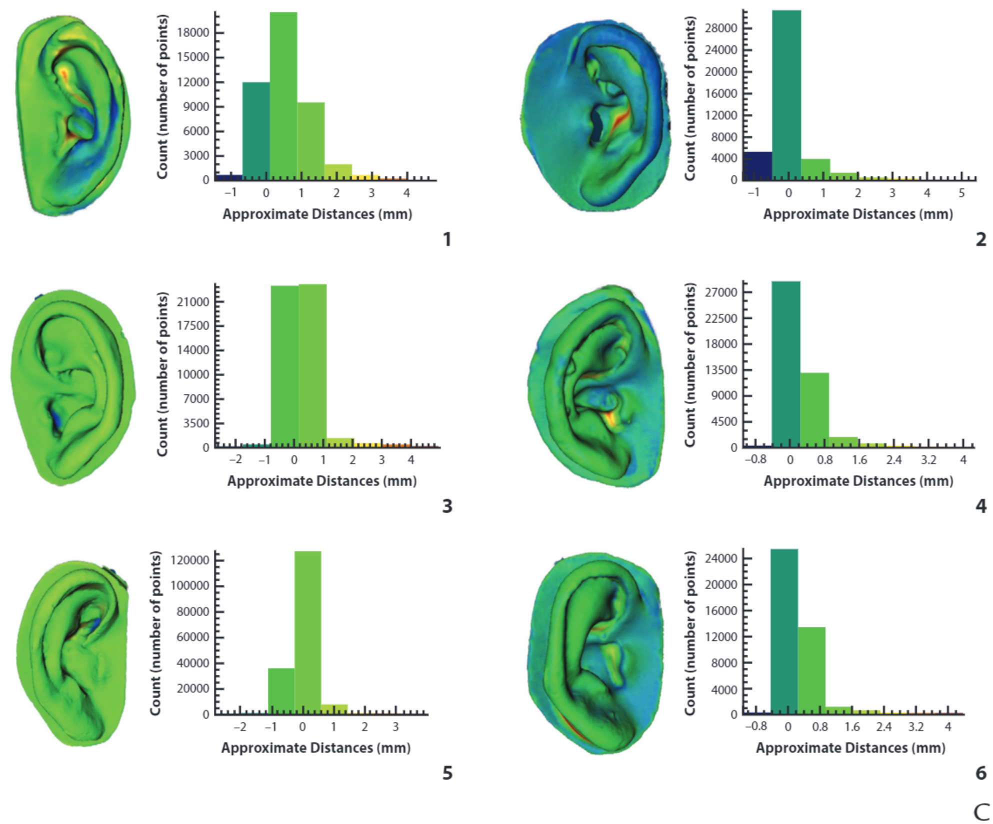

Figure 2. (*continued*). C, In test for accuracy with smartphone 2. Count refers to points in 3D cast while approximate distance (mm) refers to mismatches in comparison with laser scanner. 0=no mismatches, negative value=inadequate overlap, positive values=excess overlap.

2 (Fig. 2C) are illustrated with color maps. Most mesh triangles were within 0 to 1 mm approximate distance (0 mm = ideal), with mismatches at the inner folds of the ear for both smartphones. The data obtained during accuracy testing are provided in Supplemental Table 3, available online.

DISCUSSION

The present study found favorable accuracy and precision for smartphone-generated 3D ear casts in comparison with those generated by a desktop laser scanner. No statistically significant differences were found in the 4 virtual parameters, and therefore, the null hypothesis was accepted. The substantially large differences in surface area (F=3.67, *P*=.05) suggest variations in surface contour. This may be from overrepresentation or underrepresentation of the surface contour within the photographs.

Most previous studies relied on 75 to 120 images per cast to generate their 3D data.[5,12] While a greater number of images can improve 3D cast texture (thereby mitigating the issue of near significance found within the current study), the present study found 48 images to have acceptable virtual parameters when compared with laser scanned ear casts. The findings on interpoint mismatches (<0.50 mm) suggest that the casts generated were accurate in terms of margins in comparison with the laser scanned casts. The large standard deviations in the values suggest substantially more mismatches on the inner structures of the ear. Furthermore, spatial overlaps of 0.90 (smartphone 1) and 0.93 (smartphone 2) suggest that the smartphone-generated casts are over 90% similar to the laser scanned casts.

While previous research reported maxillofacial prostheses generated from photogrammetry to be inaccurate,[12,16] the current study found smartphones to provide accurate scanning for ear casts. The differences of outcomes may be explained by the controlled environment in which the images were made in the present study, including equidistant photographs at both angles, precise 15-degree rotations, controlled lighting environment, and automated photographs. This accuracy is consistent with that found by previous studies when success in digital prosthodontics was only obtained after controlling variables such as tongue position, light distortion, and patient restlessness.[3,17,18] Such a controlled workflow may be implemented for cost-effective desktop 3D cast scanning and digital record keeping. Furthermore, the mechanism can be scaled for clinical application, where smartphones can be used on custom-made revolving apparatus to capture 360-degree images of facial features.

Table 1. Virtual comparison for accuracy among laser scanner, smartphone 1, and smartphone 2

	Mesh Surface Area (mm^2)		
	Mean ±SD	**F-stat (df)**	**P^c**
Laser scanner	11 098.45 ±381.03	3.67 (2)	.05[a]
Smartphone 1	10 212.32 ±875.63		
Smartphone 2	10 683.05 ±231.10		
	Virtual volume (mm^3)		
	Mean ±SD	**F-stat (df)**	**P^c**
Laser scanner	32 640.68 ±2074.39	0.84 (2)	.45[a]
Smartphone 1	34 507.02 ±5702.33		
Smartphone 2	35 683.08 ±3704.11		
	Interpoint mismatches (mm)		
	Mean ±SD	**F-stat (df)**	**P^c**
Smartphone 1	0.20 ±0.17	-0.32 (10)	.76[b]
Smartphone 2	0.24 ±0.20		
	Spatial overlap		
	Mean ±SD	**F-stat (df)**	**P^c**
Smartphone 1	0.90 ±0.03	-1.73 (10)	.30[b]
Smartphone 2	0.93 ±0.02		

df, degree of freedom; SD, standard deviation. [a]One-way ANOVA. All parametric assumptions met. Kolmogorov-Smirnov test and Shapiro-Wilk test not significant (P>.05). Normally distributed data. [b]Independent sample t test. All parametric assumptions met. Kolmogorov-Smirnov test, Shapiro-Wilk test, and Levene test not significant (P>.05). Normally distributed data. [c]Significant (<.05).

Small variations such as shadows and nonblack or white backgrounds during data acquisition can substantially distort the resultant 3D casts. Most of the mismatches in this study's 3D casts were in the inner folds of the ears and were caused by unwanted shadows forming within the invaginations. Interpoint mismatches in the current study were determined by the software-generated Hausdorff distance, which effectively broke down the 3D casts into points and automatically evaluated the number of overlaps. This allowed for the assessment of the greatest distances in interpoint mismatch between nonoverlapping points.[9] Since there were varying levels of point mismatches in the inner aspects of the ears, there were greater variations in the Hausdorff distance and therefore larger standard deviations. However, the current study found the mismatches to be less than 4 mm (Fig. 2A-C). While considered clinically acceptable,[1,8] these mismatches may or may not require clinical modifications and are largely dependent on esthetic preferences. Future research should explore methods of mitigating such shadow-based mismatches that can positively impact the 3D data acquisition process of any extraoral prosthesis.

Limitations of the present study included that the test for precision only evaluated the ability of a single smartphone to repeatedly produce 3D ear casts. Smartphone 2 was introduced to the test for accuracy based on previously published findings.[12] The near-significant findings in mesh surface area indicated the need for further evaluations of the influence of lighting and camera settings on smartphone-based stereophotogrammetry. The study was limited to virtual evaluations of digital casts as opposed to actual ear prostheses. Future research should explore the accuracy and precision of a greater number of smartphones for rehabilitating various extraoral maxillofacial defects, with an immediate focus on developing and clinically evaluating the smartphone standardization method to fabricate auricular prostheses. With improved technology, smartphone-based digital maxillofacial prosthetic rehabilitation should provide a low-cost solution for clinicians in developing regions of the world.

CONCLUSIONS

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

1. Smartphone cameras used to capture 48 overlapping images of gypsum cast ear in a controlled environment generated 3D models parametrically similar to those produced by standard laser scanners.

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Corresponding author:
Dr Nafij Bin Jamayet
Division of Clinical Dentistry (Prosthodontics)
School of Dentistry, International Medical University
Jalan Jalil Perkasa-19, Bukit Jalil
Kuala Lumpur 57000
MALAYSIA
Email: dr.nafij@gmail.com

CRediT authorship contribution statement

Taseef Hasan Farook: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft. **Farah Rashid:** Data curation, Formal analysis, Investigation, Methodology. **Nafij Bin Jamayet:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing - review & editing. **Johari Yap Abdullah:** Conceptualization, Data curation, Software, Validation, Supervision. **James Dudley:** Methodology, Project administration, Validation, Writing - review & editing. **Mohammad Khursheed Alam:** Conceptualization, Project administration, Validation, Visualization, Writing - review & editing.

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