Three-Dimensional Facial Scanning at the Fingertips of Patients and Surgeons: Accuracy and Precision Testing of iPhone X Three-Dimensional Scanner

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Background: The iPhone X (Apple, Inc., Cupertino, Calif.) is the first smartphone to be released with a high-fidelity three-dimensional scanner. At present, half of all U.S. smartphone users use an iPhone. Recent data suggest that the majority of these 230 million individuals will upgrade to the iPhone X within 2 years. This represents a profound expansion in access to three-dimensional scanning technology, not only for plastic surgeons but for their patients as well. The purpose of this study was to compare the iPhone X scanner against a popular, portable three-dimensional camera used in plastic surgery (Canfield Vectra H1; Canfield Scientific, Inc., Parsippany, N.J.).

Methods: Sixteen human subjects underwent three-dimensional facial capture with the iPhone X and Canfield Vectra H1. Results were compared using color map analysis and surface distances between key anatomical landmarks. To assess repeatability and precision of the iPhone X three-dimensional scanner, six facial scans of a single participant were obtained and compared using color map analysis. In addition, three-dimensionally–printed facial masks (n = 3) were captured with each device and compared.

Results: For the experiments, average root mean square was 0.44 mm following color map analysis and 0.46 mm for surface distance between anatomical landmarks. For repeatability and precision testing, average root mean square difference following color map analysis was 0.35 mm. For the three-dimensionally–printed facial mask comparison, average root mean square difference was 0.28 mm.

Conclusions: The iPhone X offers three-dimensional scanning that is accurate and precise to within 0.5 mm when compared to a commonly used, validated, and expensive three-dimensional camera. This represents a significant reduction in the barrier to access to three-dimensional scanning technology for both patients and surgeons. (*Plast. Reconstr. Surg.* 146: 1407, 2020.)

Three-dimensional technology continues to add value in plastic surgery by providing surgeons with innovative clinical tools. In the early stages of development, three-dimensional photography and simulation were used in consultation with patients as a communication tool.[1–3] More recently, three-dimensional technology has progressed to being used in preoperative virtual surgical planning sessions and in the production of sterilized, three-dimensionally–printed guides, jigs, and reference models for intraoperative use.[4,5] Newer three-dimensional technologies on the horizon include augmented reality for intraoperative surgical navigation and virtual reality for preoperative planning of complex surgery.[6] Regardless of its application, the starting point for

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Table 1. Comparison of Commonly Used Three-Dimensional Scanners and Cameras in Plastic and Reconstructive Surgery

3D Capture System	Approximate Base Cost (USD)	Capture plus Processing Time	Portability	Realization	Accuracy (mm)
3DMDFace System[8–10]	≥$25,000	9 sec	No	Active and passive stereophotogrammetry and structured light	0.2
Canfield Vectra H1[11,12]	$13,000	90 sec	Yes	Passive stereophotogrammetry	0.2–0.3
Artec Eva 3D[13]	$15,000	25 sec	Yes	Structured light triangulation	0.2–0.4
M4D System[14]	$15,000	30 sec	Yes	Structured light triangulation	0.5
Crisalix 3D Face Simulator[15,16]	$2000–$5000 yearly	5 min	Yes	Structured light triangulation	2.0–5.0
Dimensional Imaging Di3D System[17,18]	>$25,000	60 sec	Yes	Passive stereophotogrammetry	0.2

USD, U.S. dollars.

all of these tools is the acquisition of three-dimensional data of the patient.

Although three-dimensional technology continues to grow in popularity among plastic surgeons, certain aspects of currently available three-dimensional data capture systems may limit widespread adoption and restrict access to this technology for many surgeons worldwide. The cost of the most commonly used and well-validated capture systems typically exceeds $10,000 and is often bundled with additional software that may be unnecessary and require annual maintenance contracts (Table 1).[7–18] Lack of portability and unfamiliarity with capture technology may also present a barrier for plastic surgeons seeking to incorporate three-dimensional technology into their practices. In combination, these factors may reduce overall adoption of three-dimensional technology in plastic surgery and have established the need for a low-cost, portable, and easy-to-use three-dimensional scanner.[6]

The iPhone X (Apple, Inc., Cupertino, Calif.) is the first globally distributed smartphone to feature a built-in three-dimensional scanner (Fig. 1). Starting at $699, the iPhone X three-dimensional scanner was initially designed as a security measure that uses three-dimensional scanning technology to replace passwords for user authentication and access to banking and financial applications.[19]

At present, the iPhone constitutes the largest segment of smartphones being used in the United States, with over 230 million iPhones currently in use, and recent data suggest that over half of iPhone users plan to upgrade their iPhone to the iPhone X within 2 years.[20,21] The implications of these data for three-dimensional technology in plastic surgery are profound: by the year 2020, a substantially expanded number of plastic

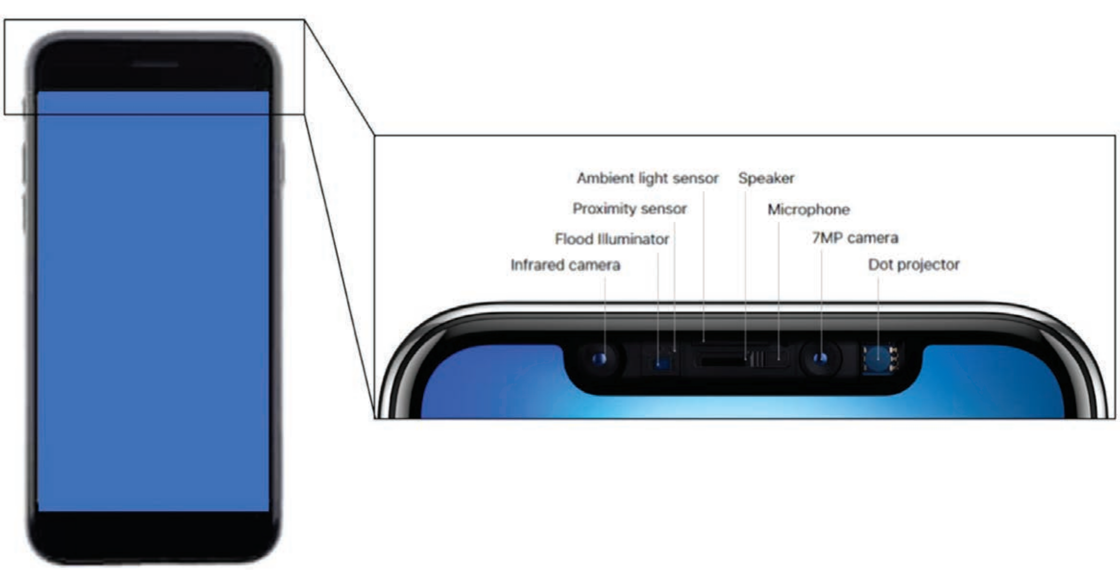

Fig. 1. Front-facing three-dimensional capture system onboard the iPhone X. The dot projector projects 30,000 infrared points on the subject and is received by the infrared camera. Color is overlaid onto each point by means of integration of the 7-megapixel camera.

surgeons and patients around the world will have access to a three-dimensional scanner. This may dramatically reduce the barrier to entry for plastic surgeons seeking to incorporate three-dimensional technology into their practices. Moreover, it may place highly accurate three-dimensional scanning technology in the hands of patients for the first time. Given these profound implications, the current study sought to assess the precision of the iPhone X three-dimensional scanner and compare the accuracy of three-dimensional scans acquired using the iPhone X to the Canfield Vectra H1 (Canfield Scientific, Inc., Parsippany, N.J.) three-dimensional capture system. The Canfield Vectra H1 is a portable three-dimensional camera that has been validated in the literature and is routinely used as a clinical and research tool for three-dimensional analysis in plastic surgery.[22–24]

METHODS

Study Protocol

Comparison between facial scans obtained with the iPhone X and Vectra H1 was performed

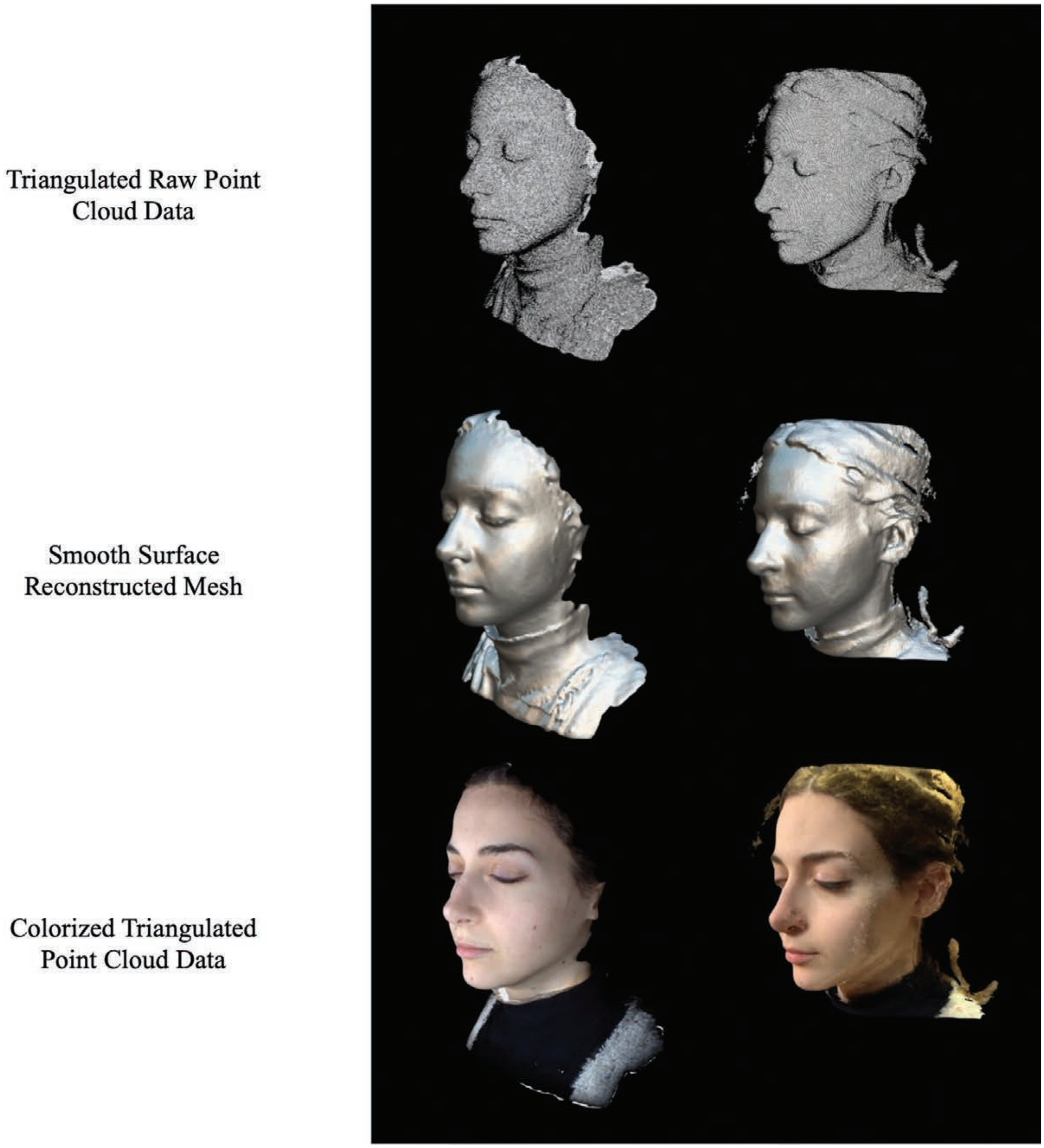

Fig. 2. Comparison between three-dimensional images obtained with the Canfield Vectra H1 (*left*) and iPhone X (*right*) systems.

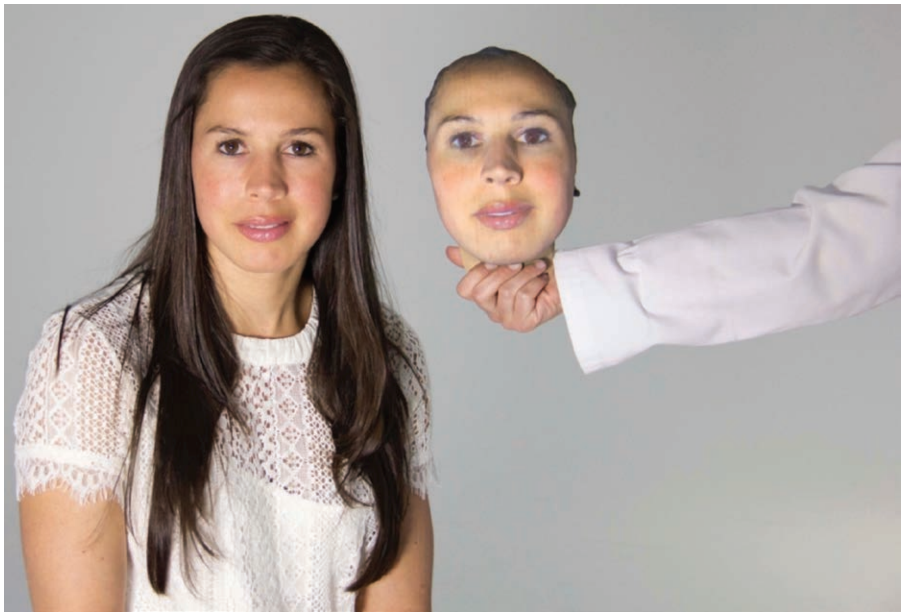

Fig. 3. Example of three-dimensionally–printed facial mask (held on right) that was scanned for the inanimate object comparison. (Used with permission from MirrorMe3D.)

on 16 unique participants (Fig. 2). Precision and repeatability of the iPhone X three-dimensional scanner were investigated by obtaining multiple facial scans (n = 4 scans) of one study participant at different time points. In addition, to limit variables related to scanning live humans that might impact the quality of a three-dimensional scan (i.e., respiration and microfacial expressions), comparison was also performed on three inanimate, multicolored three-dimensionally–printed facial masks (ProJet 660; 3D Systems, Rock Hill, N.C.) (Fig. 3).

Three-dimensional capture with iPhone X was performed by rotating the three-dimensional scanner around the patient while using a publicly available third-party iPhone application (ScandyPro, New Orleans, La.). Patients were instructed to maintain a neutral expression and to relax both their mouths and eyes to a comfortable resting position for each capture. The resulting scans were imported into three-dimensional analysis software (Vectra Analysis Module; Canfield Scientific). Unique image pairs of the same patient were established from the three-dimensional images, and color map analysis was performed for each pair as described below.

Postprocessing

All models obtained with the iPhone X scan were exported in Alias Wavefront Object (.OBJ) format and uploaded to a desktop computer. Postprocessing was performed to remove nonanatomical components such as clothing in addition to head hair using a third-party three-dimensional modeling software (Meshlab; ISTI, Pisa, Italy) and Blender (Blender Foundation, Vienna, Austria). Two functions were performed during postprocessing; cropping of the three-dimensional model to remove hair and clothing, and the application of a hole-filling function to fill holes in scans smaller than 0.3 mm in diameter (Fig. 4). Following postprocessing, iPhone X scans for each patient were imported into a three-dimensional analysis software (Vectra Analysis Module). Vectra H1 three-dimensional images were exported in .OBJ format and did not require postprocessing.

Three-Dimensional Analysis

Using the Vectra Analysis Module software, iPhone X–derived three-dimensional face models were compared with a three-dimensional model of the same patient obtained using the Canfield Vectra H1 camera. In addition, for repeatability and precision experiments, iPhone models were compared against a three-dimensional photograph obtained with the iPhone X of the same subject.

Using the three-dimensional analysis desktop software, co-registration for each image pair was performed using a native automated iterative closest point method applied to the entire three-dimensional model that has been described in the literature.[25] Following the registration, heat map/

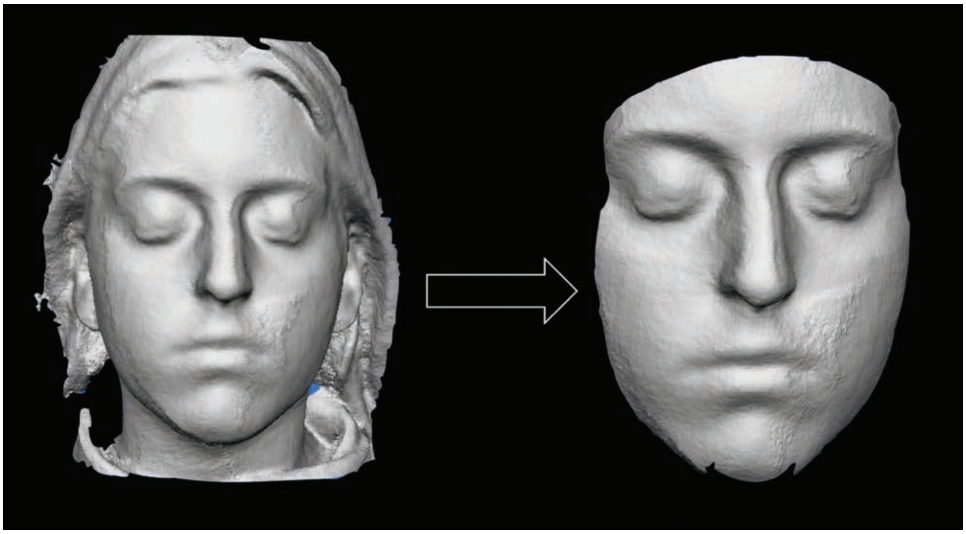

Fig. 4. Transformation of three-dimensional object following postprocessing. Unprocessed three-dimensional image (*left*) was cropped and extraneous noise removed to produce processed three-dimensional image (*right*).

color map analysis was performed by comparing the distance for each vertex on the iPhone X scan to its the closest vertex on the registered iPhone X or Vectra H1 three-dimensional image. Resulting distances were visualized as a color-coded "heat map" that has been described previously in three-dimensional capture validation studies[14,23] (Fig. 5). In addition to color map analysis, for the iPhone X versus Vectra H1 comparison, 10 anatomical landmarks were manually established on each image for each image pair. Landmarks were manually placed in the following anatomical areas of each model: the medial and lateral canthi, the radix, the supratip lobule, the oral commissure (left and right), and the midpoints of the upper and lower vermilion lines. Landmark-to-landmark surface distances were calculated for each image and compared between pairs. The distance between the two landmarks was determined using a computer algorithm that took the shortest path along the surface of the model between the landmark pairs (Fig. 6).

Statistical Analysis

All statistical analysis was performed using Microsoft Excel (Microsoft Corp., Redmond, Wash.). Root mean square values were used to calculate error in measurement between image pairs. Root mean square values are a surrogate for standard deviation around a mean, when the mean is expected to be 0. In the present study, the authors assumed an equal probability of a measurement error skewing positive or negative of 0, and thus root mean square was chosen as the ideal measure. In addition to root mean square, mean measurement error with standard deviation was also reported. This method of analysis has been reported in previous validation studies.[7,14,22] Analysis of variance testing was performed to investigate the presence of significant differences between pairs. Categorical variables were compared using chi-square tests. Significance was set a priori at $p < 0.05$ for all analyses.

RESULTS

For the iPhone X versus Vectra H1 experiment, a total of 16 participants, eight men and eight women, were recruited into the study and submitted to three-dimensional photography with the Canfield Vectra H1 camera and iPhone X. The average time for capture of each scan was 20 seconds using the iPhone X. The average age of the participants was 30 years (range, 20 to 60 years). Results of the iPhone X three-dimensional scanner versus Vectra H1 camera color map analysis are shown in Table 2 and Figure 7, *above*. Surface distance analysis demonstrated an average root mean square distance when including all image pairs of 0.46 mm. Mean measurement error following color map analysis was root mean square = 0.43 ± 0.10 mm. When considering all image pairs, the measurement error range was −2.71 to 2.71 mm. The median measurement error when considering all image pairs was 0.01 mm. For the three-dimensionally–printed facial mask, comparison between the iPhone X–obtained three-dimensional image of the mask and Vectra

Fig. 5. Registered Vectra H1–derived three-dimensional image (color) and iPhone-derived three-dimensional image (uncolored) (*left*). Color map analysis performed on iPhone-derived three-dimensional model (*center*). Isolated color map visualized on iPhone-derived three-dimensional image.

H1–obtained image generated a mean root mean square difference of 0.28 ± 0.05 mm.

The mean absolute measurement error between landmark-to-landmark surface distances on Vectra H1–derived models and the same distances performed on iPhone X–derived models was 0.46 ± 0.01 mm. When including measurements from all image pairs, analysis of variance testing identified significant differences in absolute measurement error between landmark-to-landmark pairs ($p < 0.001$). Landmark pairs 4 and 7, 7 and 9, 10 and 8, and 10 and 9 demonstrated greater absolute measurement error between iPhone X– and Vectra H1–acquired three-dimensional data.

For repeatability and precision testing of the iPhone X scanner, color map analysis demonstrated an average root mean square measurement error for all image pairs of 0.35 mm. Mean measurement error was 0.00 ± 0.35 mm. The average median measurement for all image pairs was −0.008, and when considering all pairs, the range was −1.95 to 2.07 mm. Results of the precision and repeatability experiments are shown in Table 3.

DISCUSSION

The iPhone X is a highly capable three-dimensional scanner that is already in the hands of millions of individuals in the United States and will increasingly disseminate over the next 2 years.[21] As both patients and surgeons realize the power of the tool available at their fingertips, it will become increasingly important for surgeons to understand the limitations and capabilities of the iPhone X three-dimensional scanner.

In the current study, iPhone X three-dimensional scanner precision was investigated and found to have a root mean square value of 0.35 mm, which is superior to the precision of other portable three-dimensional scanners investigated in the literature.[14] Knoops et al. investigated the precision of the Structure Sensor (Occipital, Inc., Boulder, Colo.) and M4D Scanner (Rodin 4D, Mérignac, France) and reported root mean square errors of 0.50 ± 0.04 mm and 0.51 ± 0.03 mm, respectively, following color map analysis.[14]

The current study sought to investigate the accuracy of the iPhone X with a commonly used and well-validated three-dimensional camera in plastic surgery. The Vectra H1 system is a portable three-dimensional camera that has been validated against the 3dMDface system (3dMD, Inc., Atlanta, Ga.), a high-end, stationary three-dimensional scanning system that has been used as a control group in several validation studies for three-dimensional scanners, and was found to have an average root mean square distance of 0.20 to 0.43 mm after color map analysis.[7,13,22,26,27] To date, no formal guidelines have been proposed with regard to a threshold of accuracy for three-dimensional data acquisition systems to be used clinically. Nonetheless, Vectra H1 has been used for three-dimensional data acquisition in several

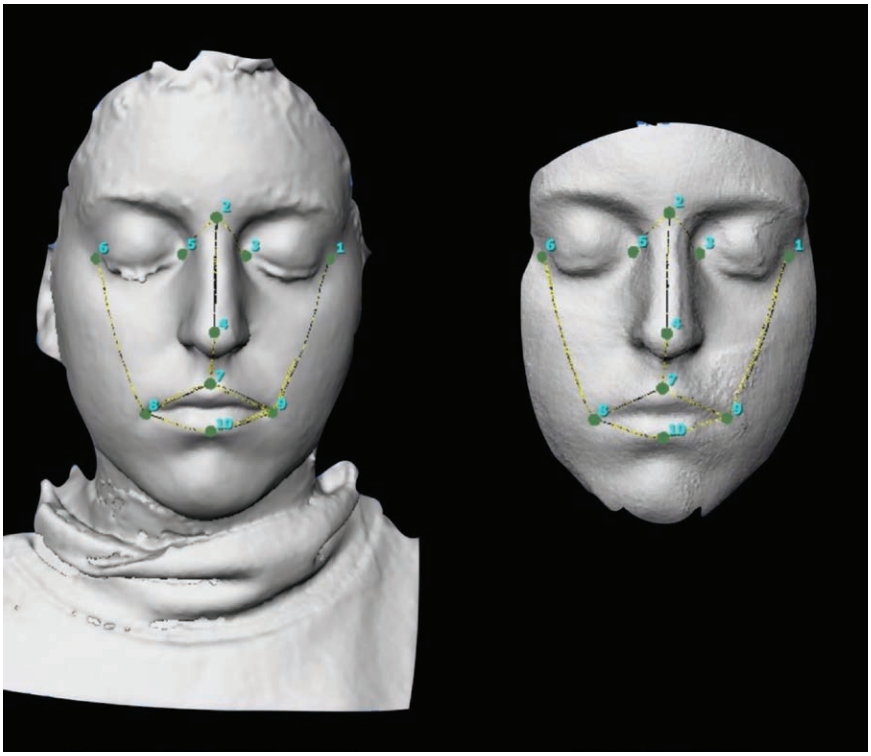

Fig. 6. Identical landmarks were identified on the Vectra H1 three-dimensional image (*left*) and iPhone X three-dimensional image (*right*). Landmark-to-landmark shortest distance across the surface of the model was performed for each image, and these measurements were compared.

three-dimensional analysis studies published in the plastic surgery literature and is routinely used in clinical settings in plastic surgery.[23,24,28]

Our study identified significant differences in surface distances between landmark-to-landmark pairs. Landmark pairs 4 and 7, 7 and 9, 10 and 8, and 10 and 9 demonstrated greater absolute measurement error between iPhone X– and Vectra H1–acquired three-dimensional data when considering all participants. The facial areas investigated by these areas corresponded with the oral commissures and the eyelids (Fig. 7, *below*). These findings are consistent with the presence of changes in facial microexpression and rapid eye movements that occur between scans and has been described previously in the literature, which may result in deviations between scans.[11,29]

To distinguish between live human-related factors and scanner-related factors in the present study, we also performed three-dimensional analysis of three static three-dimensionally–printed human facial masks that were captured with both the iPhone X and the Vectra H1 camera. This analysis demonstrated markedly improved agreement between the two scans, indicating that live-human factors including respiration during scanning and facial microexpression during and between scans do indeed have an effect on the outcome of the

Table 2. Results of Precision and Repeatability Analysis through Color Map Distance Analysis following Registration of the Three-Dimensional Image Pairs of the Same Participant Taken with the iPhone X*

Comparison Group	Minimum	Maximum	RMS	Mean	SD	Median
1 vs. 2	−1.97	2.66	0.41	0.01	0.41	0.00
1 vs. 3	−2.11	2.01	0.38	0.01	0.38	0.00
1 vs. 4	−2.17	3.22	0.45	0.01	0.45	−0.01
2 vs. 3	−2.14	1.45	0.26	−0.01	0.26	0.00
2 vs. 4	−1.46	1.34	0.26	0.00	0.26	−0.01
3 vs. 4	−1.85	1.77	0.34	−0.02	0.34	−0.03
Average	−1.95	2.07	0.35	0.00	0.35	−0.01

RMS, root mean square.
*Data units are in millimeters.

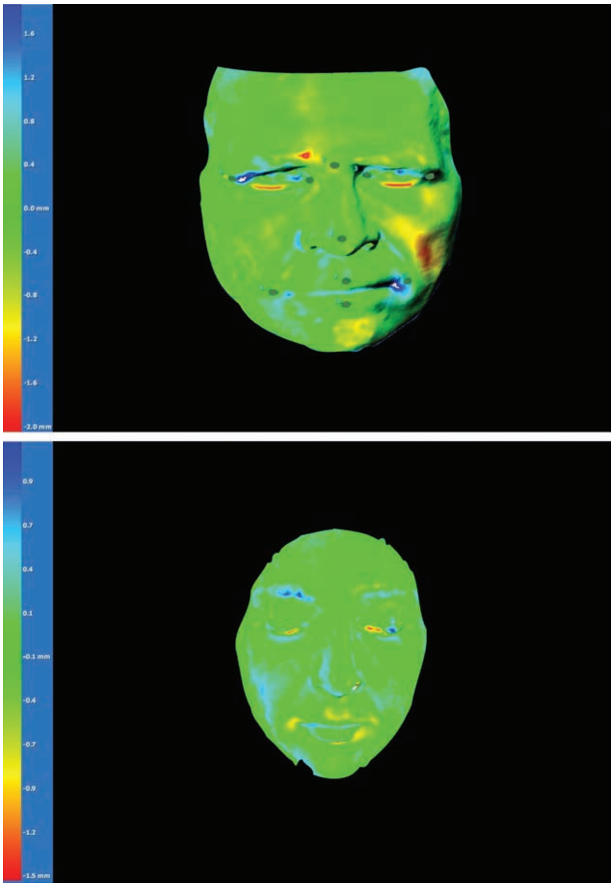

Fig. 7. (*Above*) Color map results for participant 2. Left-handed color-coded bar represents the deviation between the iPhone and Vectra-derived scans in millimeters. (*Below*) Magnification of color map demonstrating deviations in the oral commissures and eyelids; areas of the face consistent with changes in facial microexpression and rapid eye movement occurring during and between capture with the Vectra H1 and the iPhone X devices.

three-dimensional scan. In the present study, the authors advised participants to assume a neutral, easy-to-maintain resting facial expression. In the clinical setting, it is advisable that surgeons similarly attempt to minimize facial motion during scanning. One factor not investigated in this study was the impact of patient-specific variables on the accuracy of the scan. For example, it is therefore possible that for obese patients and in patients with increased facial fat (e.g., Cushing syndrome), it may be more difficult to obtain accurate measurements compared to patients with fewer and less dramatic skin folds on the face.

With respect to the internal technology, the iPhone X scanner uses a front-facing infrared laser system to acquire precise topographic three-dimensional data and a front-facing optical camera to acquire color information. The system was designed in part as a security tool for user identification and therefore may be optimized for facial scanning. To acquire three-dimensional data, the iPhone three-dimensional scanner, commonly referred to as the TrueDepth Camera by Apple, Inc., uses a laser that projects 30,000 unique infrared points on the user's face and captures the distance of these points from the device using a separate sensor.[19] An onboard ambient light projector and optical camera are used to enhance the capture of these data and to overlay color onto the three-dimensional model reconstructed from the infrared points. In the present study, the authors chose to use ScandyPro as the application for data acquisition because it was felt that this application provided accurate scans because of the ability to interact with a minimally edited mesh created

Table 3. Results of Color Map Distance Analysis following Registration of the Vectra H1– and iPhone X–Obtained Three-Dimensional Image for Each Participant*

	Minimum	Maximum	RMS	Mean	SD	Median
Subject						
1	−3.22	3.43	0.62	0.02	0.61	0.05
2	−5.95	2.85	0.46	0.00	0.46	−0.02
3	−2.02	3.20	0.63	0.02	0.63	0.00
4	−2.44	2.23	0.46	0.08	0.45	0.04
5	−1.77	2.45	0.42	0.00	0.42	0.00
6	−2.27	2.71	0.44	−0.02	0.44	−0.02
7	−1.48	1.20	0.23	0.01	0.23	0.01
8	−1.77	2.71	0.45	−0.04	0.44	−0.04
9	−2.44	2.43	0.40	0.00	0.33	0.01
10	−1.25	1.83	0.27	0.03	0.27	0.01
11	−2.71	2.49	0.43	−0.01	0.43	0.04
12	−1.99	2.60	0.43	0.01	0.43	0.00
13	−2.76	2.57	0.49	0.05	0.49	0.05
14	−2.67	2.60	0.54	−0.02	0.54	0.01
15	−2.12	2.60	0.34	0.06	0.34	0.04
16	−2.08	1.83	0.40	0.03	0.40	0.04
Mean ± SD	−2.43 ± 1.07	2.48 ± 0.53	0.44 ± 0.10	0.01 ± 0.03	0.43 ± 0.11	0.01 ± 0.03

RMS, root mean square.
*Data units are in millimeters.

from the raw point cloud data obtained by the scanner.

The learning curve associated with capturing three-dimensional images with the iPhone X has several advantages over the Vectra H1. The Vectra H1 requires the user to obtain three photographs using a digital single-lens reflex camera at specific angles and by aligning multiple lights projected from the camera on the face of the patient. To individuals unfamiliar with this process, this may pose a challenge to learning how to correctly obtain a three-dimensional photograph. In comparison, the iPhone X uses a simple point-and-capture method based on the front-facing scanner, and individuals familiar with using the front-facing camera of any smartphone (i.e., taking a selfie) will find the process of obtaining a three-dimensional scan to be similar. In addition, most individuals are already familiar with the iPhone X hardware and interface, which makes it easier for novices in three-dimensional scanning to obtain an accurate three-dimensional scan when compared to more complex three-dimensional capture systems on the market.

There are also important differences in the learning curve when considering the computer software used to analyze the three-dimensional scans. In our study, we used Vectra Analysis Module, MeshLab, and Blender to compare Vectra H1 and iPhone X images. Vectra Analysis Module is part of a software package that surgeons typically purchase with the Vectra H1. MeshLab and Blender, however, are capable of performing many of the same three-dimensional analyses and are free to download and use. In addition, many free three-dimensional modeling software programs maintain robust online communities that are dedicated to teaching new users how to use these powerful and free software packages. One disadvantage of these free software packages, however, is that there are no out-of-the-box solutions available to surgeons to perform three-dimensional manipulations that relate specifically to plastic surgery (i.e., simulation rhinoplasty). This is not the case in commercial software packages such as Vectra Analysis Module, where surgeons can manipulate the anatomical features of the patient using intuitive buttons. Nonetheless, it is possible to perform similar manipulations using free software, albeit with more user input and greater familiarity with the three-dimensional modeling tools available within the software.

Importantly, as compared to the cost of a Vectra camera and corresponding computer-aided manufacturing software (approximately $10,000), the cost of acquiring three-dimensional data with the iPhone X was negligible. Downloading the iPhone three-dimensional scanning application used in the present study was free, although users must pay for the option to export the three-dimensional scans from the application to their personal computers so that the three-dimensional images can be analyzed using the free software package described. The rates offered for the ability to export scans using the application in the study are $1.99 for unlimited exportations within 1 week, $5.99 for 1 month, and $49.99 for 1 year. As noted above, we used two free software packages to analyze the three-dimensional photographs on a desktop computer in our study. These software packages, MeshLab and Blender, are powerful three-dimensional modeling software programs that when coupled to a low-cost iPhone three-dimensional scanning technology create opportunities for substantial cost savings when compared to nearly all other three-dimensional data acquisition systems (Table 1). One other encouraging point is the recent expansion of three-dimensional scanning technology to mobile devices including those using Android technology.

Presently, a number of popular mobile devices including Android phones are investing in three-dimensional scanning technology, which will further increase accessibility to this technology. Currently, the Samsung Galaxy S9 and S9 plus contain a high-quality three-dimensional scanner that is used for facial recognition. Samsung has also released its plans for the Galaxy Note 10 to contain an advanced DepthVision three-dimensional scanner coupled with a Samsung-produced free three-dimensional scanning application that will contain features such as direct export to desktop three-dimensional printers. Samsung has also noted that they intend to use the three-dimensional scanner for augmented reality applications as well.[30]

There are several limitations to our study. Although we report encouraging statistics with narrow standard deviation distributions relating to the accuracy of the iPhone scanner, the data reported in this study are largely descriptive. This is similar to other studies reported in the literature that are widely cited and support the use of other three-dimensional imaging devices in a clinical setting. Nonetheless, given the limited sample size in the present study and the nature of the study design, these data do not statistically prove equivalence between the two devices. Another important limitation of the current study was the decision to focus only on the face and no other areas of the body. There were two reasons for this. First, the Vectra H1 is only capable of capturing the face in three dimensions and is not capable of capturing other parts of the body such as the breast, extremities, or trunk. Second, given the design behind the iPhone X three-dimensional scanner as a user facial authentication security tool, we chose to use human faces as our target object for three-dimensional capture in the current study, as it was assumed that this would be the highest performing anatomical area with respect to accuracy. Given this, readers should exercise caution in extrapolating the accuracy of the iPhone X reported in the study to other anatomy. Future studies will evaluate the iPhone X as a tool for three-dimensional scanning nonfacial anatomy such as the breast, trunk, and extremities.

In summary, the iPhone X is capable of producing three-dimensional facial scans with an accuracy resulting in an average difference of less than 0.5 mm when compared against images obtained with the Canfield Vectra H1. In addition, the repeatability and precision of the iPhone X scanner are superior to those of most three-dimensional capture systems used in plastic surgery, with an average difference of less than 0.5 mm between scans of the same object. These data are encouraging and imply that a highly capable three-dimensional data acquisition system will be in the hands of many millions of patients and thousands of plastic surgeons worldwide in the coming 2 years. This imminent reality lowers the barrier to entry for obtaining three-dimensional scans and will likely translate into increased incorporation of three-dimensional technology into plastic surgery in the coming years.

CONCLUSIONS

The iPhone X outperforms most portable three-dimensional data acquisition systems currently available on the market when considering accuracy and precision. Many patients and plastic surgeons will already find themselves with the hardware required to begin acquiring highly accurate three-dimensional models in the near future. The additional costs and learning curve associated with using the iPhone X as a three-dimensional scanner are minimal. The capability of the iPhone X to acquire accurate and precise three-dimensional data represents the first marked reduction in the barrier to entry for using three-dimensional technology for both patients and plastic surgeons.

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PARTICIPANT CONSENT

Participants provided written consent for the use of their images.

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