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Breast

Potential of Intraoperative 3D Photography and 3D Visualization in Breast Reconstruction

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Background: Although pre- and postoperative three-dimensional (3D) photography are well-established in breast reconstruction, intraoperative 3D photography is not. We demonstrate the process of intraoperative acquisition and visualization of 3D photographs for breast reconstruction and present clinicians' opinions about intraoperative visualization tools.

Methods: Mastectomy specimens were scanned with a handheld 3D scanner during breast surgery. The 3D photographs were processed to compute morphological measurements of the specimen. Three visualization modalities (screen-based viewing, augmented reality viewing, and 3D printed models) were created to show different representations of the 3D photographs to plastic surgeons. We interviewed seven surgeons about the usefulness of the visualization methods.

Results: The average time for intraoperative acquisition of 3D photographs of the mastectomy specimen was 4 minutes, 8 seconds ± 44 seconds. The average time for image processing to compute morphological measurements of the specimen was 54.26 ± 40.39 seconds. All of the interviewed surgeons would be more inclined to use intraoperative visualization if it displayed information that they are currently missing (eg, the target shape of the reconstructed breast mound). Additionally, the surgeons preferred high-fidelity visualization tools (such as 3D printing) that are easy-to-use and have minimal disruption to their current workflow.

Conclusions: This study demonstrates that 3D photographs can be collected intraoperatively within acceptable time limits, and quantitative measurements can be computed timely to be utilized within the same procedure. We also report surgeons' comments on usability of visualization methods and of measurements of the mastectomy specimen, which can be used to guide future surgical practice. *(Plast Reconstr Surg Glob Open 2021;9:e3845; doi: 10.1097/GOX.0000000000003845; Published online 7 October 2021.)*

INTRODUCTION

Although pre- and postoperative imaging are well-established tools in plastic surgery, intraoperative imaging for plastic surgery applications is less wide-spread and used most often for assessing fracture repair outcomes, navigating complex anatomical structures, and monitoring perfusion in breast reconstruction.[1–6] Likewise, three-dimensional (3D) photography has been limited to pre- and postoperative use because the imaging systems were large and lacked mobility. However, recent advances, including the availability of portable 3D photography systems, present opportunities to acquire 3D images intraoperatively to aid surgeons during reconstruction surgery. Researchers are continuing to demonstrate the accuracy and usability of mobile and handheld systems for collecting 3D photographs, especially for facial applications, such as rhinoplasty.[7–10] However, more validations of these systems are needed for additional intraoperative applications. The aim of this study was to demonstrate how to

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assess the feasibility of intraoperative 3D photography and visualization modalities, such as 3D printed models and augmented reality (AR), in reconstructive surgery applications.

Recent advances in visualization tools have enabled new intraoperative uses of 3D images acquired either pre- or intraoperatively. Visualization methods that provide 3D information are especially valuable in plastic surgery applications and include tools such as 3D printing and augmented reality. In reconstructive surgery, 3D printed models have been used as intraoperative guides and measurement tools for surgeons during procedures such as auricular reconstruction,[11] calvarial vault reconstruction,[12] craniofacial reconstructions,[13] and breast reconstruction.[8,14–16] 3D printed breast molds created with preoperative 3D surface images of patients' breasts and designed for surgeons to determine the amount of autologous tissue needed to shape the flap into the form of the new breast have been tested by researchers for autologous reconstructions. Other researchers have created physical models of abdominal vasculature to guide surgeons in locating the desired perforators in the tissue flap. 3D printing using intraoperative rather than preoperative images has been limited by concerns about printing time, which depends on the size, complexity, and necessary details of the model for the application.

Augmented reality visualizations consist of virtual elements integrated into the real-life environment and can be implemented with heads-up displays, head-mounted displays, and direct projections. Previous reviews of augmented reality in plastic surgery have discussed a variety of applications, methods, and tools.[17–19] Intraoperative uses of augmented reality in surgery mostly used head-mounted displays, devices that are worn on the head that display virtual elements over the surgeon's view, as well as heads-up displays, devices such as TV monitors that display a video of the surgical field. The virtual elements were often preoperative imaging or surgical plans superimposed onto the surgical field. Other studies used tracking systems to highlight certain anatomical structures or surgical instruments. Most applications were in craniofacial surgeries, but also included perforator tracking in breast reconstructions, endoscopies, and vasculature repair.[17–19] Augmented reality technologies continue to advance with more user-friendly devices and sophisticated software, which increases the opportunities for incorporating intraoperative imaging with intraoperative visualization.

The purpose of this study was to demonstrate the process of intraoperatively acquiring and processing 3D photographs, using immediate autologous breast reconstruction as an exemplar application. We also solicited the opinions of plastic surgeons on the usability of intraoperative visualization tools for the operating room. 3D photographs of mastectomy specimens can be obtained with a handheld 3D scanner after the specimen has been removed from the chest wall by the breast surgeon. The mastectomy specimen images can then be processed and displayed to the plastic surgeon while preparing the autologous flap. Previous studies suggest that the mastectomy specimen can aid the reconstructive surgeon in shaping the autologous flap by providing information such as the spatial distribution of the native breast volume.[15,16,20,21] The potential long-term benefit of the use case is a reduction in the number of revisions procedures required to achieve an acceptable outcome, which could increase utilization of autologous breast reconstruction. Our data support the utility of incorporating intraoperative 3D photography and intraoperative visualizations in reconstructive surgery for surgical decision-making.

Takeaways

Question: Is it feasible to intraoperatively acquire and visualize 3D photographs in breast reconstruction?

Findings: 3D photographs of mastectomy specimens can be efficiently acquired during breast surgery and efficiently prepared for visualization during immediate breast reconstruction surgery. Reconstructive surgeons were interviewed to provide their opinions about the potential of different tools for visualizing 3D photographs during reconstructive surgery.

Meaning: This research provides a framework for future applications of intraoperative 3D photography and visualization.

METHODS

Intraoperative Acquisition of 3D Photographs

The study sample consisted of 12 breast cancer patients undergoing mastectomy at The University of Texas MD Anderson Cancer Center. 3D photographs of 14 specimens were acquired under an IRB-approved protocol, and participants provided written informed consent.

Immediately after removal, specimens from complete and partial mastectomies were laid out and oriented on a back table in the operating room. A Go!Scan 3D Scanner (Creaform, Levis, Canada) was used to acquire 3D photographs of the specimens. Up to four images of each of the 14 specimens were obtained before the specimen was taken for pathology evaluation (Fig. 1). We recorded the time to position each specimen for imaging, to capture and render each image, and the total time taken for the imaging process, including all preceding items.

MeshLab[22] was used to evaluate the quality of the 3D photographs. Raw images, which included the surfaces of the specimen and tabletop, were imported into MeshLab, and lateral and top views were rendered as shown in Fig. 2. Image quality was assessed by measuring the number of holes in the surface mesh.

Preprocessing of 3D Photographs for Intraoperative Display

The images were processed to compute morphological measurements of the specimen. The image processing workflow is shown in Figure 3. Mesh smoothing[23,24] was performed to remove local surface details while still maintaining the global topology. A custom mesh crop algorithm was used to segment the mastectomy specimen from the tabletop. We used surface curvature and distance metrics

Fig. 1. Imaging of complete mastectomy specimen intraoperatively using Go!Scan 3D camera system. The breast surgeon placed the specimen on the imaging table for the research assistant to orient and scan before delivery of the specimen to pathology. The average imaging procedure time was 4 minutes, 8 seconds ± 44 seconds.

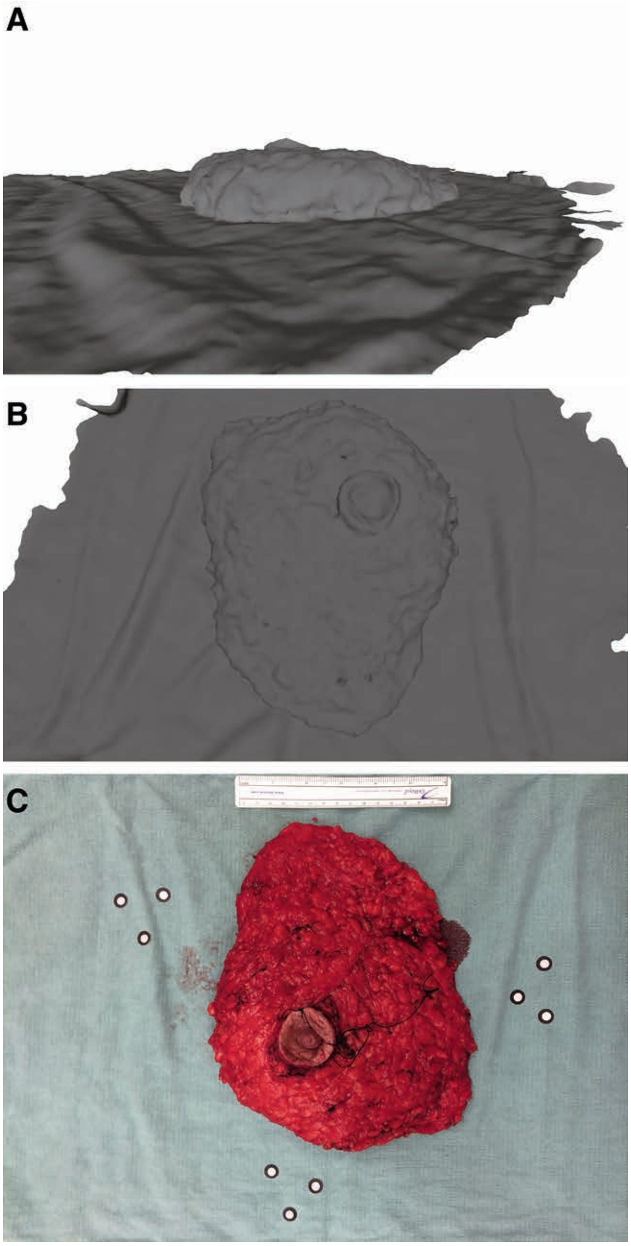

Fig. 2. 2D and 3D images of mastectomy specimens. A, B, 3D images of complete mastectomy specimen: lateral and top views. The images were rendered in Meshlab.[22] C, 2D image of complete mastectomy specimen: top view.

to detect the boundary points and applied a convex hull algorithm to determine a continuous boundary. (**See figure 1, Supplemental Digital Content 1,** which displays (a) the unprocessed scanned image of a mastectomy specimen. (b) Image after mesh smoothing in Meshlab.[22] **http://links.lww.com/PRSGO/B788**.) All vertices inside the identified boundary were marked as mastectomy specimen and those outside the boundary were marked as table, thus segmenting the specimen surface from the tabletop surface. A backplane was created to close the segmented mesh using an algorithm developed by our group[25] and advancing front mesh technique (**See figure 2, Supplemental Digital Content 2,** which displays (a) Gaussian curvature of surface. Flat regions are green, concave regions are blue and convex regions are red. (b) Detected boundary points (blue) and convex hull enclosing the boundary points (red) of mastectomy specimen. (c) Segmented specimen. (d) Closed back plane. **http://links.lww.com/PRSGO/B789**.)

We computed the height, width, and length profiles of each specimen by projecting the surface image of the specimen onto 2D planes. The most protruding point in the Z direction was identified as the nipple. We then determined the medial, lateral, inferior, and superior radii by drawing straight lines from the nipple point to the horizontal and vertical margins of the specimen (Fig. 4). The volume of the specimen was computed using a previously defined algorithm.[26]

Usability Interviews with Plastic Surgeons

To gauge the usability and acceptance of the intraoperative visualizations, we conducted semistructured interviews with plastic surgeons from The University of Texas MD Anderson Cancer Center to determine their opinions about the usefulness of three visualization modalities: screen-based viewing of 3D photographs, augmented reality viewing, and 3D printed models. We used preprocessed 3D photographs of two differently shaped mastectomy specimens for the visualizations. The data were collected under an IRB-approved protocol, and all surgeons provided verbal consent to participate.

Visualization Modalities

The screen-based viewing modality consisted of showing 2D pictures of the 3D photographs of the specimen,

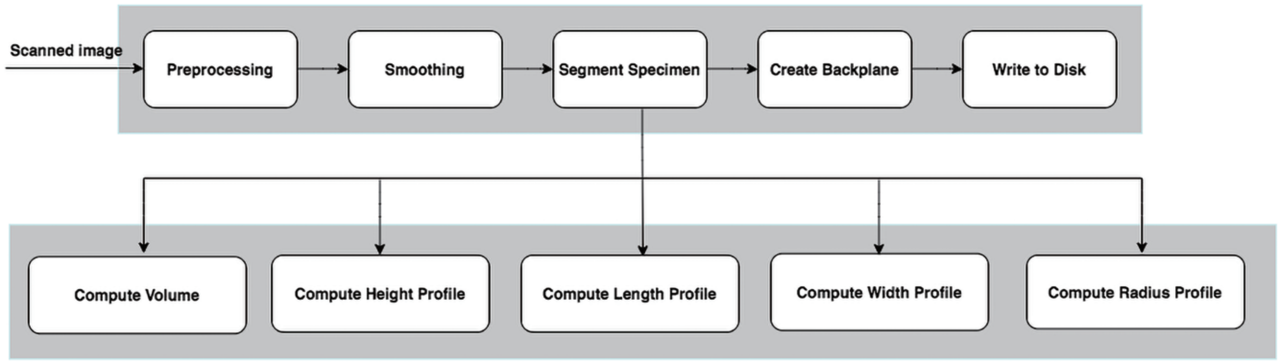

Fig. 3. Workflow describing the steps involved in processing and analyzing the scanned image.

a movie of a rotating 3D photograph, and an interactive 3D photograph using the MeshLab application on a tablet. The surgeons were informed that the visualizations could be adapted for a TV or computer screen. The 2D pictures included measurements of the specimen labeled on the image, and the movie listed measurements beside the rotating image (Fig. 5). The interactive model displayed no measurements. We created a Microsoft HoloLens application for visualization of the specimen "holograms" and measurements using augmented reality. The application supported rotation, translation, and scaling of the holograms, allowing them to be moved and pinned to any desired spatial location. Two different measurement display schemes were used for each exemplar specimen image (Fig. 6). The surgeons were able to view and interact with the four holograms after a brief usage tutorial. A variety of 3D printed models were created to demonstrate the options available with 3D printing. Five models were created with a Stratasys 3D printer (Stratasys, Minneapolis, Minn.), and two models were created with a Craftbot XL 3D printer (CraftUnique, LLC, Stillwater, Okla.). The models had varying levels of smoothing, filling density, colors, and scale. Three high-fidelity models had print times of approximately 8 hours. Four models were created with the goal of attaining a printing time of less than 2 hours, requiring either a low fill density, a half-scale model, or a model made in multiple, contiguous sectional portions that were glued together when complete (Fig. 7). As 3D printing technologies are evolving rapidly, operational times and

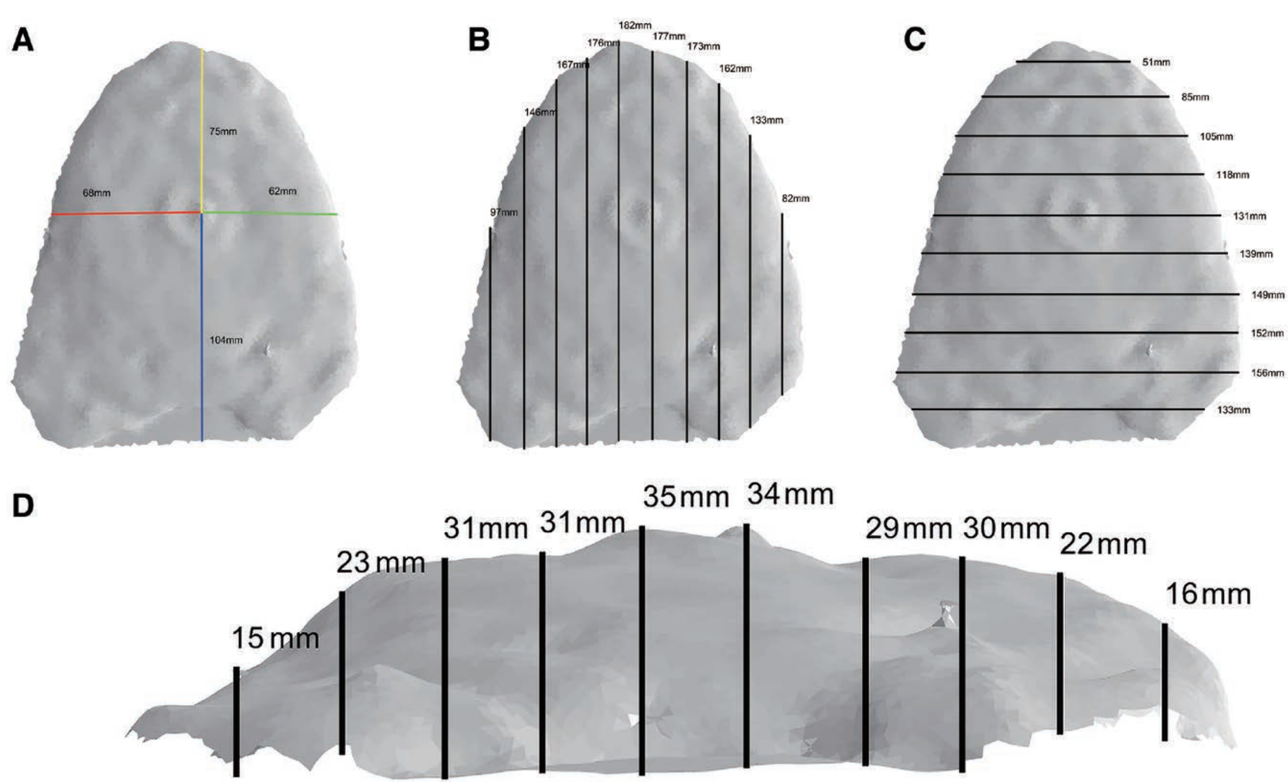

Fig. 4. Results from image processing performed for automated computation of specimen measurements. A, Radius profile (yellow: superior radius, blue: inferior radius, green: medial radius, red: lateral radius). B, Length profile. C, Width profile. D, Height profile.

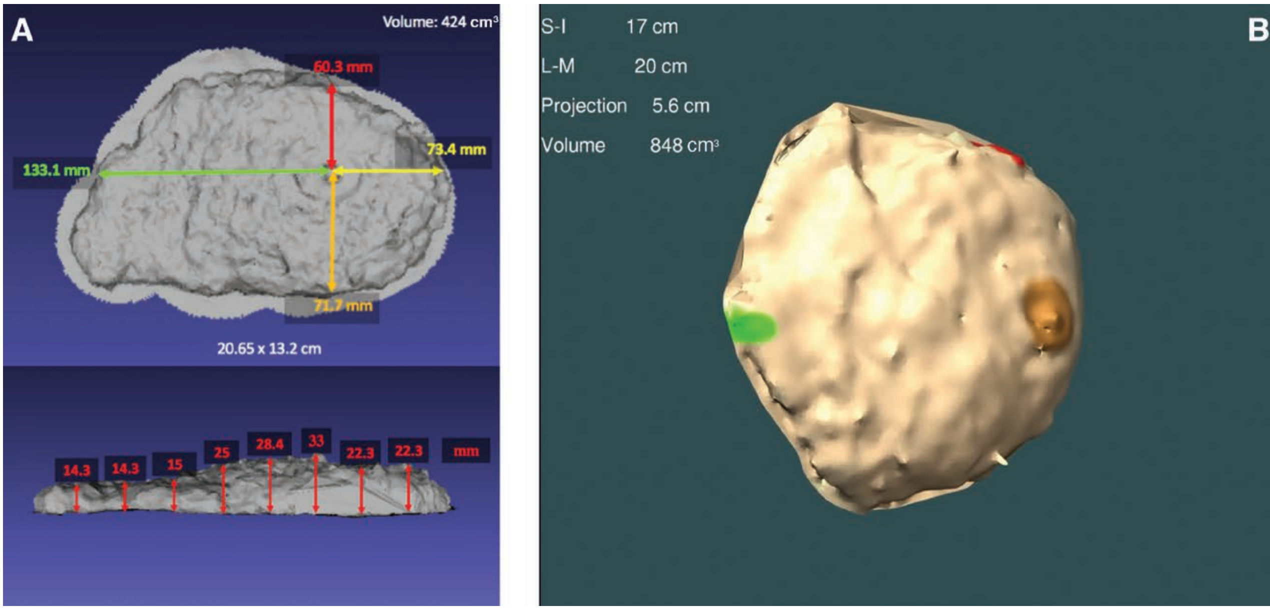

Fig. 5. Screen-based viewing visualizations presented to surgeons on a tablet during the usability interviews. A, 2D pictures of the 3D photographs with measurements. B, A screenshot of a movie of a rotating 3D photograph.

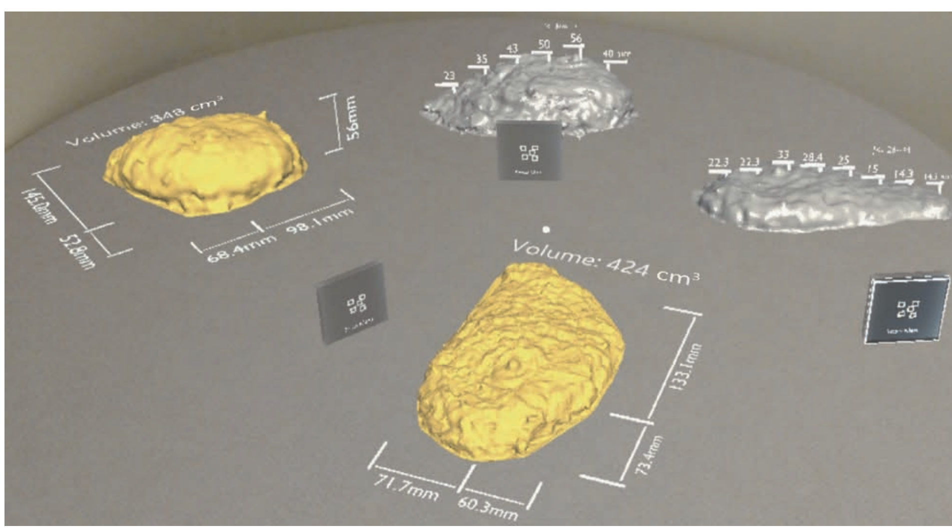

Fig. 6. Augmented reality visualization presented to surgeons with the Microsoft HoloLens during usability interviews. Four holograms represent two mastectomy specimens with two different measurement schemes. The holograms can be translated, rotated, and resized with hand gestures. The measurements of the yellow holograms in the figure are from the nipple to specimen margins. The grey holograms show the height profiles of the specimens. Note that the Go!Scan photography system used for this study did not capture texture, and the texture displayed in the visualizations was chosen by the researchers.

costs are expected to improve, so that future applications could use a 3D printer that creates a high-fidelity, sterilizable model in a smaller amount of time.

Interview Setting and Structure

Surgeons were recruited through word of mouth and departmental announcements. The interviews took place in an office setting, requiring the surgeons to imagine using the tools intraoperatively. The surgeons were asked to discuss whether and how they would use each modality intraoperatively, and what improvements might be made, and to complete the System Usability Scale (SUS)[27] for each modality. The SUS is a 10-item Likert-scale questionnaire that assesses effectiveness, efficiency, and satisfaction for a tool or system.

RESULTS

3D Image Acquisition and Processing

3D Photography is Fast Enough for Intraoperative Use

Setting up the scanning environment, including placing positioning targets and plugging in the scanner, took

Fig. 7. 3D printed visualization presented to surgeons during the usability interviews. Several models were provided, representing varying levels of smoothing, filling density, colors, and scale. This model was created with the Craftbot XL 3D (CraftUnique, LLC, Stillwater, Okla.) in four sections, which were glued together to demonstrate a printing option with reduced printing time.

less than 3 minutes. As shown in Table 1, among the 14 specimens, the average time to orient the specimen was approximately 23 seconds; the average time to scan the specimen was approximately 40 seconds; and the average time to render the image was approximately 16 seconds. The average total procedure time was 4 minutes, 8 seconds ± 44 seconds. The scan time generally decreased over the course of the experiment as the research assistant gained experience with the technology. (**See figure 3, Supplemental Digital Content 3,** which shows that the amount of time needed to complete a scan of the mastectomy specimen tended to decrease as the research assistant completed more scans. The x-axis represents the 56 scans in chronological order. The y-axis is the time required to complete the scan. The dashed line is a simple linear fit with $y = -0.3774 + 50.375$ and $R^2 = 0.2761$. **http://links.lww.com/PRSGO/B790**.)

3D Photography Can Provide Acceptable Image Quality

Ideally, medical image quality assessment is task based[28,29]; so the ultimate question is how useful the images are to the surgeons. Here, we performed a rudimentary quality evaluation as a preliminary assessment. Non-manifold vertices were deleted first and then the number of holes in each image was determined (mean, 6.34 ± 5.78).

Rapid Image Processing Can Be Achieved

We recorded the elapsed time at each step in the processing workflow (Table 2). The average time to execute the image processing pipeline was 54.26 ± 40.39 seconds, with 14.31 ± 2.52 seconds on average being needed to process the unsegmented image and an average of 39.94 ± 37.86 seconds needed for creation of the backplane and computation of specimen metrics. An automated image processing pipeline, such as used in this study, provides the software assistance required for fast computation of the features without manual interference. However, certain scenarios, such as collapsing of the nipple areola complex region, might render erroneous results for automated detection of the nipple. Such scenarios warrant manual verification and correction of the computed measurements. Such validations can be easily performed using open source tools such as MeshLab.[22]

Table 1. Acquisition Time of 3D Images (n = 56)

Procedure	Average Time (s)
Orient specimen	23.10 ± 10.07
Scan specimen	39.62 ± 11.71
Render and save image	15.76 ± 6.40
Total procedure time	248.05 ± 44.26

Table 2. Average Execution Time for Each Step in the Processing Pipeline

Image Type	Processing Step	Average Time (s) ± SD
Unprocessed image	Preprocess	03.14 ± 0.49
	Smooth	00.21 ± 0.03
	Segmentation	10.95 ± 1.99
	Total	14.31 ± 2.52
Segmented image	Create backplane	29.02 ± 29.34
	Write to disk	00.009 ± 0.008
	Height profile	00.14 ± 0.05
	Length profile	00.14 ± 0.04
	Width profile	00.14 ± 0.04
	Radius profile	00.08 ± 0.01
	Volume	10.40 ± 8.35
	Total	39.94 ± 37.86
	Total execution time	54.26 ± 40.39

Surgeon Interviews

Seven plastic surgeons completed the interview and questionnaires. The average number of years postfellowship was three (range 1–29); two identified as women, and five identified as men.

Perceived Cost–Benefit Ratio of New Technology

A low cost-to-benefit ratio was key for the surgeons' willingness to adopt a new technology. All of the interviewed surgeons commented that they would be more inclined to use intraoperative visualization technologies if they displayed a type of information they were currently missing. For example, in the immediate autologous breast reconstruction scenario, some surgeons said that they would like to be able to visualize the vasculature information on the patient's body or the target shape of the reconstructed breast. The surgeons had mixed opinions about the usefulness of the mastectomy specimen beyond its weight. The simplest, easiest-to-use visualization mode was preferred over other modes that necessitated prior training. For example, one surgeon commented "3D printed models are the best because I don't have to learn anything to use it" (Table 3).

Preserving Workflow Is a Priority

Minimal disruption to the current workflow must be a priority design consideration for any intraoperative tool, especially in terms of sterility, impact on the surgeon, and impact on patient care. Sterility considerations influenced three surgeons to prefer a TV screen over an interactive display amongst the conventional viewing tools. The HoloLens' primary negative aspect was the weight of the device, impacting the surgeon's comfort

Table 3. Usability Interview Findings

Cost–Benefit Ratio		Preserving Workflow				
Benefit to Patient Care	**Ease of Use**	**Sterility**	**Impact on Surgeon**	**Impact on Patient Care**	**Tool Complexity**	**High-fidelity**
"The HoloLens is neat but I don't right now see the benefit it provides, I think something like this [iPad] with measurements is just as useful."	"I wouldn't use it [screen-based viewing] a lot because I'm not used to it."	"As long as I don't have to touch anything, it's better."	"It's [HoloLens] cumbersome to put on, it's heavy, it's going to take some time… Getting it situated on your head so you can actually see something, that was cumbersome."	"Ideally, I'd want to see it before I'm in the OR...this is kind of hard to stop mid-case to look at it."	"The thing I'm thinking about is when we do these flaps, we base them on these tiny blood vessels that are incased in fat tissue, so we have to like very carefully, like layer by layer dissect towards them without destroying them, so it would be cool if we had that and we could see through the fat and know when we were coming up to them."	"Can you 3D print something using a material more like silicone or like a gel that's not hard?"
"People are willing to trade off and use this stuff if it's going to significantly help. For example, we will take all our stuff off and we will go the microscope during the surgery because it's absolutely necessary and it significantly improves your surgery…Right now I don't see that level of benefit."	"[3D printed model] is easy to use. The surgeon doesn't have be an innovator to adopt it."	"The mastectomy specimen will likely come out when I'm physically scrubbed so there's a workflow component to that so it would probably have to be on a screen."	"I don't how useful it would be to stop what I'm doing to put this on."	"Let's say you say 'we can only give it to you in the operating room'…Put it on a big screen TV, that way I can discuss it with my team."	"This device would need to be improved considerably…smaller, more full screen, precalibrated, which I could do myself before the surgery, so it would be literally just put it on and see this."	"What I'm seeing doesn't look like a mastectomy specimen… it's like playdoh." [HoloLens]
"It's not the technology [limiting use], it's the point of reference, mastectomy specimen versus donor site [type of information presented]."	"Of everything you showed me, the easiest thing is to just show a picture, the 2D pictures."	"It's another 2 minutes to actually go rescrub, so I don't think it's that too big of a deal if it turns out using this is helpful."	"As it is now, I couldn't do a surgery wearing it [HoloLens] the whole time."		"I could see how if I could take that and spin it in the operating room and look at my patient and spin it against the patient, I could see how that could be, I'd be like' yeah like there it is, that's what I need to do' and I could make adjustments in real time. That would be helpful."	"I think in most anatomy books the breast is yellow and that's what it is in real life, so that might be better received."

and mobility. The surgeons also expressed concern that patient care could be impacted by time delays resulting from using a 3D printed model or the HoloLens. They noted they would use these methods more with preoperative information, when there was more time to prepare the visualization. Surgeons who placed a higher value on the mastectomy specimen information were more willing to accept the time delay needed to create a 3D printed model.

Response Variation with Tool Complexity

The more complex HoloLens yielded more critiques, suggestions for change, and varied personal preferences than the simpler conventional viewing or 3D printed tools. When evaluating the HoloLens, the surgeons made more remarks, such as expressing preferences for the appearance of the virtual model, increasing the field of view, simplifying the hand gestures, and manipulating of the model. The amount of time spent discussing the HoloLens tool ranged from 27% to 45% of the total interview time.

Preference for High-fidelity Visualizations

The surgeons expressed a desire for high-fidelity visualizations. When discussing the appearance of the mastectomy specimen, surgeons suggested that the specimen model have an anatomical color or a color commonly used in medical texts. No surgeon found the half-sized 3D printed model to be useful or acceptable, and two surgeons asked whether the texture of the 3D model could be soft, mimicking real tissue. In addition, interaction with the visualization increased acceptability. For the conventional viewing tools, the surgeons rated the interactive mode higher than passive images. They also rated the 3D printed model higher than the image-based visualizations.

System Usability Scale Results

The SUS questionnaire results agreed with the interview findings showing that less complex visualization tools are easier to use and are more readily adoptable (Table 4). The 3D printed models and screen-based viewing methods had similar average usability scores of 77.5 ± 13 and 76.4 ± 11 (scale of 0–100). The HoloLens received a significantly

Table 4. System Usability Scale Results

SUS Question	Average Surgeon Response (N = 7)		
	HoloLens	Screen-based	3D Models
1. I think that I would like to use this system frequently	3.00	3.71	3.14
2. I found the system unnecessarily complex	3.10	1.40	2.10
3. I thought the system was easy to use	2.86	3.86	4.00
4. I think that I would need the support of a technical person to be able to use this system	3.71	1.71	1.14
5. I found the various functions in this system were well integrated	3.60	3.40	3.20
6. I thought there was too much inconsistency in this system	2.40	2.10	1.10
7. I would imagine that most people would learn to use this system very quickly	3.14	4.29	4.43
8. I found the system very cumbersome to use	3.40	2.10	1.70
9. I felt very confident using the system	2.90	4.30	4.10
10. I needed to learn a lot of things before I could get going with this system	2.90	1.60	1.30
Overall Average Score	49.60	76.40	77.50
SD	15.80	10.60	13.10

Respondents answered each question from 1 (strongly disagree) to 5 (strongly agree).

lower average score of 49.6 ± 16 owing to both the difficulty of wearing the device and the complexity of the system. The individual sub-items with the greatest difference in scores between the HoloLens and other methods were "I found the system unnecessarily complex," "I think I would need the support of a technical person to use this system," and "I found the system cumbersome to use." Although the SUS is a convenient scale for assessing usability, the surgeons had difficulty answering the item "I found the various functions in this system were well integrated" for the 3D printed models and screen-based methods as they do not appear to have multiple components.

DISCUSSION

It is undisputed that 3D photography can be valuable for objective and quantitative documentation of plastic surgery outcomes. Many prior studies have analyzed 3D photographs of breast reconstruction patients during pre- and postoperative visits.[30–32] Some studies have also combined preoperative 3D photographs with magnetic resonance imaging data for intraoperative use.[33,34] However, only one other study acquired 3D photographs during surgery (reduction mammoplasty).[35] We demonstrated that 3D photographs can be acquired during reconstruction surgeries within acceptable time limits. Intraoperative 3D photography must be very fast to be practical because the operating room charge alone can exceed $100 per minute.[36–38] We achieved consistent image quality with an average imaging time of around 4 minutes.

This study also demonstrated that quantitative measurements can be computed from intraoperative 3D photographs quickly enough to be used within the same surgery. Although currently there are no standard procedures for obtaining metrics from 3D photographs used in the operating room, prior studies have employed various measurement techniques from preoperative imaging to facilitate flap shaping,[20,39,40] which is a good starting point for future intraoperative imaging applications. We created an exemplar workflow for intraoperative image processing and calculation of measurements from intraoperative 3D photographs. This framework provides a basis for developing custom workflows in future studies.

Several methods proposed here are promising for 3D visualization during reconstructive surgery. All of the surgeons we interviewed emphasized that the most important factor impacting their interest in adopting an intraoperative visualization technology is whether or not it displays information that they want to see. The surgeons disagreed about the usefulness of the mastectomy specimen information, with some suggesting that perforator location or a final breast model would be more useful. Although there are several exciting studies about the application of mixed reality in surgery,[17–19] most of the surgeons we interviewed still prefer traditional visualization methods. Their primary concern with mixed reality tools such as the HoloLens is that complexity of use (including the mechanics of wearing the device while interacting with the system) would outweigh the information gained.

In addition, we presented usability data for the surgical application that we adopted as a test case for intraoperative 3D photography and intraoperative 3D visualization: imaging and visualizing the mastectomy specimen during immediate autologous breast reconstruction. Prior work suggests that information about the mastectomy specimen can help surgeons more accurately shape the flap during autologous breast reconstruction.[20,21] Theoretically, the new breast mound will match the preoperative form if the TRAM flap is a replica of the mastectomy specimen. Studies such as those by Tomita et al[15] and Ahcan et al[39] have used 3D photography and intraoperative visualization for unilateral and delayed autologous reconstruction cases. An intraoperative 3D photograph of the mastectomy specimen allows for more careful measurements of the specimen when the actual specimen has to be evaluated for pathology, as well as more accurate measurements compared with a preoperative scan. Most surgeons in our study agreed that mastectomy specimen weight and volume are useful information, and some thought that topological information about the mastectomy specimen as obtained from a 3D photograph could also be helpful. However, the surgeons' preferences regarding visualization of the mastectomy specimen varied considerably. For example, some said that they would want to see the 3D photograph of the specimen superimposed on the chest wall. The surgeon interviews highlighted the importance of multidisciplinary collaboration between engineers and healthcare professionals to successfully incorporate new technology, especially in the surgical setting.

The next stages of this research include investigating visualizations that will aid surgical decision-making, such as resizing the intraoperative mastectomy specimen photograph for patients who want to change their breast size. In addition, a cost–benefit study could be conducted to measure the increase in surgical time and effort to use the intraoperative visualization versus the impact on subsequent revision procedures. Intraoperative 3D photography and visualizations can be investigated for other applications such as patient and trainee education, planning contralateral revision procedures, and improving partial breast reconstruction.

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REFERENCES

1. Wilde F, Schramm A. Intraoperative imaging in orbital and midface reconstruction. *Facial Plast Surg.* 2014;30:545–553.
2. Borad V, Lacey MS, Hamlar DD, et al. Intraoperative imaging changes management in orbital fracture repair. *J Oral Maxillofac Surg.* 2017;75:1932–1940.
3. Chan HH, Siewerdsen JH, Vescan A, et al. 3D rapid prototyping for otolaryngology-head and neck surgery: applications in image-guidance, surgical simulation and patient-specific modeling. *PLoS One.* 2015;10:e0136370.
4. Phillips BT, Lanier ST, Conkling N, et al. Intraoperative perfusion techniques can accurately predict mastectomy skin flap necrosis in breast reconstruction: results of a prospective trial. *Plast Reconstr Surg.* 2012;129:778e–788e.
5. Schrögendorfer KF, Nickl S, Keck M, et al. Viability of five different pre- and intraoperative imaging methods for autologous breast reconstruction. *Eur Surg.* 2016;48:326–333.
6. Lee BT, Matsui A, Hutteman M, et al. Intraoperative near-infrared fluorescence imaging in perforator flap reconstruction: current research and early clinical experience. *J Reconstr Microsurg.* 2010;26:59–65.
7. Knoops PG, Beaumont CA, Borghi A, et al. Comparison of three-dimensional scanner systems for craniomaxillofacial imaging. *J Plast Reconstr Aesthet Surg.* 2017;70:441–449.
8. Mayer HF. The use of a 3D simulator software and 3D printed biomodels to aid autologous breast reconstruction. *Aesthetic Plast Surg.* 2020;44:1396–1402.
9. Modabber A, Peters F, Kniha K, et al. Evaluation of the accuracy of a mobile and a stationary system for three-dimensional facial scanning. *J Craniomaxillofac Surg.* 2016;44:1719–1724.
10. Koban KC, Perko P, Etzel L, et al. Validation of two handheld devices against a non-portable three-dimensional surface scanner and assessment of potential use for intraoperative facial imaging. *J Plast Reconstr Aesthet Surg.* 2020;73:141–148.
11. Flores RL, Liss H, Raffaelli S, et al. The technique for 3D printing patient-specific models for auricular reconstruction. *J Craniomaxillofac Surg.* 2017;45:937–943.
12. LoPresti M, Daniels B, Buchanan EP, et al. Virtual surgical planning and 3D printing in repeat calvarial vault reconstruction for craniosynostosis: technical note. *J Neurosurg Pediatr.* 2017;19:490–494.
13. Nyberg EL, Farris AL, Hung BP, et al. 3D-printing technologies for craniofacial rehabilitation, reconstruction, and regeneration. *Ann Biomed Eng.* 2017;45:45–57.
14. Hummelink S, Verhulst AC, Maal TJJ, et al. Applications and limitations of using patient-specific 3D printed molds in autologous breast reconstruction. *Eur J Plast Surg.* 2018;41:571–576.
15. Tomita K, Yano K, Taminato M, et al. DIEP flap breast reconstruction in patients with breast ptosis: 2-stage reconstruction using 3-dimensional surface imaging and a printed mold. *Plast Reconstr Surg Glob Open.* 2017;5:e1511.
16. Jablonka EM, Wu RT, Mittermiller PA, et al. 3-DIEPrinting: 3D-printed models to assist the intramuscular dissection in abdominally based microsurgical breast reconstruction. *Plast Reconstr Surg Glob Open.* 2019;7:e2222.
17. Sayadi LR, Naides A, Eng M, et al. The new frontier: a review of augmented reality and virtual reality in plastic surgery. *Aesthet Surg J.* 2019;39:1007–1016.
18. Guha D, Alotaibi NM, Nguyen N, et al. Augmented reality in neurosurgery: a review of current concepts and emerging applications. *Can J Neurol Sci.* 2017;44:235–245.
19. Yoon JW, Chen RE, Kim EJ, et al. Augmented reality for the surgeon: systematic review. *Int J Med Robot.* 2018;14:e1914.
20. Garcia O Jr. The mastectomy specimen as a model for TRAM flap fabrication in immediate breast reconstruction. *Ann Plast Surg.* 1999;42:27–32; discussion 32.
21. Maximovich S. DO as the artists and sculptors do: the mastectomy specimen as a model to finalize tram flap shape in immediate breast reconstruction. *Plast Reconstr Surg.* 1996;97:483.
22. Cignoni P, Callieri M, Corsini M, Dellepiane M, Ganovelli F, Ranzuglia G. MeshLab: an open-source mesh processing tool. In: Scarano V, Chiara RD, Erra U, eds. Paper presented at Eurographics Italian Chapter Conference. The Eurographics Association; 2008.
23. Kroon D-J. Smooth Triangulated Mesh. https://www.mathworks.com/matlabcentral/fileexchange/26710-smooth-triangulated-mesh. Accessed March 25, 2021.
24. Desbrun M, Meyer M, Schröder P, Barr AH. Implicit fairing of irregular meshes using diffusion and curvature flow. In: *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques.* SIGGRAPH ’99. ACM Press/Addison-Wesley Publishing Co.; 1999:317–324.
25. Cheong AL. Computational modeling of breast shape using spherical harmonics. Doctoral Thesis, University of Houston. Published online 2018. Available at http://hdl.handle.net/10657/3591. Accessed September 2, 2021.
26. Passalis G, Theoharis T, Miller M, Kakadiaris IA. Noninvasive automatic breast volume estimation for post-mastectomy breast reconstructive surgery. In: *Proceedings of the 25th*

Annual International Conference of the IEEE Engineering in Medicine and Biology Society (IEEE Cat. No.03CH37439). Vol 2; 2003:1319–1322.
27. Brooke J. SUS-A quick and dirty usability scale. In: *Usability Evaluation in Industry*.1st ed. Boca Raton, FL: CRC Press; 1996;189:4–7.
28. Fryback DG, Thornbury JR. The efficacy of diagnostic imaging. *Med Decis Making*. 1991;11:88–94.
29. Wagner RF, Weaver KE. Special historical reprint: An assortment of image quality indexes for radiographic film-screen combinations–can they be resolved? Myers K, Chen W, eds. *J Med Imag*. 2014;1(031013).
30. O'Connell RL, Stevens RJ, Harris PA, et al. Review of three-dimensional (3D) surface imaging for oncoplastic, reconstructive and aesthetic breast surgery. *Breast*. 2015;24:331–342.
31. Bauermeister AJ, Zuriarrain A, Newman MI. Three-dimensional printing in plastic and reconstructive surgery: a systematic review. *Ann Plast Surg*. 2016;77:569–576.
32. Sampathkumar U, Nowroozilarki Z, Reece GP, et al. Review of quantitative imaging for objective assessment of fat grafting outcomes in breast surgery. *Aesthet Surg J*. 2021;41(Suppl 1):S39–S49.
33. Ghaderi MA, Heydarzadeh M, Nourani M, et al. Augmented reality for breast tumors visualization. *Annu Int Conf Ieee Eng Med Biol Soc*. 2016;2016:4391–4394.
34. Gouveia PF, Costa J, Morgado P, et al. Breast cancer surgery with augmented reality. *Breast*. 2021;56:14–17.
35. Yang Y, Mu D, Xu B, et al. An intraoperative measurement method of breast symmetry using three-dimensional scanning technique in reduction mammaplasty. *Aesth Plast Surg*. Published online March 23, 2021.
36. Ting NT, Moric MM, Della Valle CJ, et al. Use of knotless suture for closure of total hip and knee arthroplasties: a prospective, randomized clinical trial. *J Arthroplasty*. 2012;27:1783–1788.
37. Childers CP, Maggard-Gibbons M. Understanding costs of care in the operating room. *Jama Surg*. 2018;153:e176233.
38. Childers CP, Showen A, Nuckols T, et al. Interventions to reduce intraoperative costs: a systematic review. *Ann Surg*. 2018;268:48–57.
39. Ahcan U, Bracun D, Zivec K, et al. The use of 3D laser imaging and a new breast replica cast as a method to optimize autologous breast reconstruction after mastectomy. *Breast*. 2012;21:183–189.
40. Rosson GD, Shridharani SM, Magarakis M, et al. Three-dimensional computed tomographic angiography to predict weight and volume of deep inferior epigastric artery perforator flap for breast reconstruction. *Microsurgery*. 2011;31:510–516.