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Presentation

Virtual 3-dimensional modeling as a valuable adjunct to aesthetic and reconstructive breast surgery

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Abstract

Three-dimensional (3D) imaging technology currently is used by various commercial industries as a method for analyzing objects and shapes. Recent work from our group and others offer data to support the use of 3D imaging as a valuable tool in aesthetic and reconstructive breast surgery. We have developed a system for creating 3D breast models that provides clinical data that can help guide surgical management. With 3D breast models, surgeons are able to visually assess the size, shape, contour, and symmetry of the breast, as well as obtain quantitative breast measurements and volumetric calculations. Three-dimensional imaging may be applied to various plastic surgery procedures including breast reconstruction with implant/tissue expanders, local flap reconstruction, free-flap reconstruction, breast augmentation, and breast reduction surgery. The novel application of 3D imaging in these settings represents a significant advance from traditional approaches to aesthetic and reconstructive breast surgery in which surgical procedures are based on 2-dimensional photographs and visual size estimates.

Keywords: Breast; Breast reconstruction; Breast surgery; Breast augmentation; Breast reduction; Plastic surgery; Breast imaging; Three-dimensional imaging

Over recent years 3-dimensional (3D) imaging technology has been developed as a novel technique for analyzing objects and shapes. Continued improvements in the quality of both 3D imaging hardware and software has led to its widespread application in various fields ranging from the automotive, aeronautical, entertainment, and archeologic industries. Three-dimensional imaging technology is used frequently by these and other specialties to perform commercial tasks such as quality inspection, custom manufacturing, reverse engineering, and digital archiving.

The medical field also has the potential to benefit from advances in 3D imaging. This technology is used routinely today within the fields of dentistry and oral surgery as a tool for creating customized dental implants or bone substitutes. Despite these examples, 3D imaging has been studied only in a select few medical specialties to date.

Surgical fields in which 3D modeling may offer unique advantages include aesthetic and reconstructive breast surgery [1]. These procedures are founded on principles of symmetry, but the ability of the modern-day plastic surgeon to assess breast contour, shape, and volume remains largely subjective. The development of techniques for performing such tasks in an objective manner would therefore be of tremendous clinical value for plastic surgeons. Recent work from our group (unpublished data) and others offer data to support the use of 3D imaging as a novel tool in breast surgery. This article highlights these discoveries and their potential clinical impact in reconstructive and aesthetic breast surgery.

Three-Dimensional Technology

Three-dimensional hardware

A number of different 3D imaging systems are available to consumers today, most are based on either laser scanning, stereophotogrammetry, or a combination of both. The methodology of stereophotogrammetry resembles that of human eye physiology, in which depth perception is achieved by

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2 eyes that perceive the same image from slightly different views. With stereophotogrammetry, paired cameras rely on the triangulation of disparate images to produce depth values, and corresponding images are then matched in space to create a 3D image [2]. Laser systems are based on similar methods of triangulation but use a laser light source to scan the object and convert it to a surface model. The specific advantages of each system depends on its intended use because scanners differ in factors such as ease of use, speed of data acquisition, requirement for postprocessing, ability to capture texture, and spatial accuracy. Furthermore, the size of 3D scanners varies greatly, ranging from a single hand-held portable device to machines that serve as rooms to accommodate/scan large equipment or the entire human body [3].

Our group has shown that successful 3D breast images can be obtained using a laser-based 3D scanner (Konica Minolta Vivid 910, Ramsey, NJ). This camera uses laser triangulation in which a plane of light from the source aperture scans the patient's torso. This light then is reflected off of the subject's skin and thus derives a surface image. The scanner captures the entire area in approximately 2 seconds and then converts the surface shape to a polygon lattice of roughly 300,000 points. Similar to most commercially available scanners today, the laser scanner system is limited by its inability to capture a 360° view of an object. For inanimate objects, industries have developed turntable systems for generating a circumferential view of the object. Because this is impractical for human patients, we have developed a system for obtaining multiple views to obtain a complete view of a patient's breasts (Fig. 1A).

The 3D scanner is attached to a tripod head that can be adjusted in height. While the camera is level with the breast, patients are asked to stand in 5 different positions for a scan: +90°, +45°, 0°, −45°, and −90° relative to the lens of the camera. The camera is lowered to the floor and 5 additional inferior views are obtained at the same angles (Fig. 1B). Kovacs et al [4] recently reported a similar technique with the use of multiple views to generate a 3D surface model of the breast. This technique of obtaining inferior views has proven especially useful for large ptotic breasts that tend to create shadowing and prevent capture of the lower pole and inframammary fold (IMF). In addition, we have found that lighting plays an important role in the quality of the images, and therefore we use fluorescent lights to illuminate the breasts and to help minimize shadowing. Last, it is important to note that we chose to scan patients standing with their arms at their side because this upright view represents the true anatomic position of the breasts.

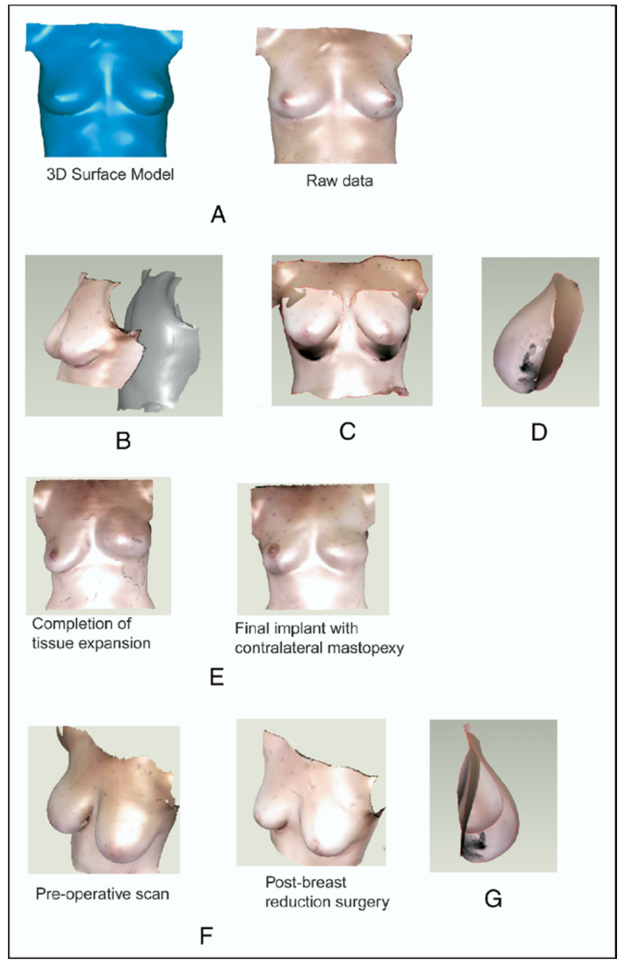

Fig. 2. (**A**) Representative image of the raw data and surface images obtained from a laser 3D scanner. (B) Demonstration of a patient's true surface image alongside her chest-wall template. (**B**) An overlay of the 2 images is created, and (**C**) this then creates the breast as a closed object so that volumetric analysis can be performed. (**D**) A representative image of an isolated breast with the back surface is shown. (**E**) Images from a patient during the final expansion period and after the exchange of the implant for a permanent implant and the contralateral mastopexy. (**F**) Images from a breast-reduction patient are shown before and after the procedure. (**G**) An overlay of the preoperative and postoperative breast is shown.

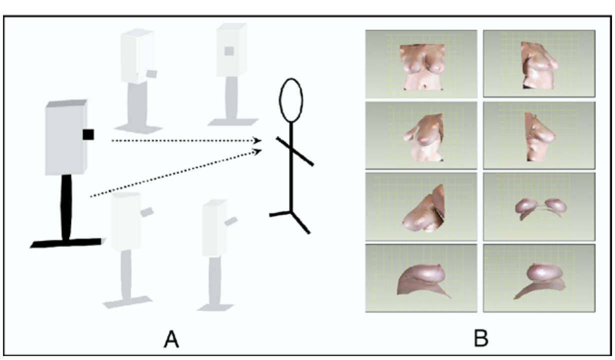

Fig. 1. (**A**) The 3D laser scanner is attached to a tripod head that can be adjusted in height. While the camera is level with the breast, images are taken from 5 different positions: with the patient +90°, +45°, 0°, −45°, and −90° relative to the camera's source. The camera then is lowered to the floor and 5 additional inferior views are obtained at the same angles. (**B**) Representative breast images of scans taken from the various angles.

Raw images that are captured by the scanner then can be processed into a 3D breast model using 3D computer software (Fig. 2A). Three-dimensional imaging software also is used for data analysis and therefore serves as an important component of the overall scanning system. Most scanners provide either their own 3D computer software or compatible third-party software, and the majority of these programs enable images to be stored in shareable formats. If images are taken from multiple angles (as shown in Fig. 1), 3D imaging software can be used to merge the individual images. For instance, programs may provide a merging function that enables one to manually identify corresponding points on each image. The computer then can overlay the images into the same special relationship, and this step can be repeated on subsequent images until a single 3D model is created.

Of note, the ideal scanning system would be composed of multiple cameras placed at various angles such that a single image could be obtained, thus preventing the need to merge multiple images. However, this type of system may be impractical given the size and cost of most cameras today (the single camera system ranges from approximately \$20,000–\$100,000). However, more affordable and compact systems currently are being developed and are likely to be on the market soon.

Three-dimensional software

Once a completed 3D surface model has been created, it can be manipulated and viewed in an infinite number of planes. This manipulation allows the surgeon to visually assess the size, shape, contour, and symmetry of the breast. In addition, quantitative breast measurements and calculations can be made using basic tools provided by 3D imaging software. Clinical data that can help guide surgical management include surface area, surface distance measurements, and breast volume. Examples of surface measurements that are useful to plastic surgeons are the distance from the nipple to the sternal notch, the distance between the nipples, the distance of the sternal notch to the IMF, and the areola diameter.

Volumetric measurements also are valuable to plastic surgeons and can be made from 3D breast models. To calculate breast volume, one must define the borders of the breast and create a closed object. One obstacle to this is defining a posterior plane of the breast (representing the chest wall) that is both accurate and reproducible. Standard software tools for creating either flat or curved planes may be used to isolate the breast for volume calculation. Other techniques for creating the posterior chest wall can be based on mathematic surface equations such as Bezier curves, nonuniform rational B-splines, and coons patches. Losken et al [5] have reported their experience with breast volume measurements using a coons patch, which creates a surface from curved boundaries that is based on repeatedly subdividing surfaces to create a representative plane. Our group has developed a system in which we create an individualized chest wall template for each patient that can be used for volumetric calculation. This template is shaped by defining the boundaries of the breast; superiorly where the breast projects from the chest wall, medially at the most medial extent of the IMF, laterally at the most lateral extent of the IMF, and inferiorly at the lowest pole of the breast. The breast then is extracted and the chest wall is recreated with a curvature-based patch. By overlaying the 3D breast images with the patient's chest-wall template, volumetric calculations can be performed (Figs. 2B–D). Of note, this chest-wall template is used for postoperative scans and to keep our measurements consistent throughout.

Clinical Applications

Breast reconstruction surgery

As the incidence of breast cancer continues to increase, breast reconstruction continues to play an integral role in breast cancer treatment. In the year 2004 alone, an estimated 63,000 women underwent reconstructive breast surgery in the United States (www.plasticsurgery.org). Despite significant progress in techniques and surgical options for breast reconstruction, one obstacle that continues to limit the overall success of breast reconstruction is the inability of plastic surgeons to objectively determine breast volume and symmetry. Today's plastic surgeon relies on standard 2-dimensional photos and visual size estimates to plan his/her reconstruction. This variability may result not only in poor surgical outcomes, but also often leads to the significant morbidity of subsequent revision procedures.

Interestingly, one of the most successful industrial applications of 3D imaging has been reverse engineering, which aims to manufacture products in which blueprints are not available but can be re-created based on 3D images. This practice of reverse engineering in many ways mimics that of breast reconstruction, which attempts to reconstruct identical (ie, symmetric, equal, and so forth) breasts after mastectomy procedures. Three-dimensional imaging analysis can help in surgical planning by providing volume measurements that are clinically useful, and were previously unattainable, to reconstructive surgeons.

In the case of unilateral mastectomy with implant breast reconstruction, one can determine baseline breast volume (BBV) on the contralateral side, which can serve as a target volume for reconstruction. Surgeons also have the ability for the first time to determine residual breast volume (RBV), or the amount of residual tissue (ie, skin and fat) remaining after the mastectomy procedure (RBV = BBV − mastectomy weights). Because this residual tissue ultimately contributes to the newly constructed breast, it is an important consideration for surgeons. Because 3D imaging allows for the calculation of RBV and target volume, these values can help the surgeon determine the appropriate size of the implant. With this knowledge, the reconstructive surgeon is empowered to make a better decision regarding the initial tissue expander size and the total volume of expansion. Comparison of the expanded volume and the contralateral BBV assists in determining the ideal implant size and the amount of tissue resection for the contralateral breast surgery (Fig. 2E).

Postoperative analysis of the implant reconstruction can help to identify the level of breast symmetry achieved and the potential need for revision procedures. This application of 3D imaging to assess postoperative results is similarly advantageous in other forms of reconstruction with free flaps or local flaps, which also may require revision procedures. Isogai et al [6] recently showed the use of 3D imaging analysis in breast reconstruction. They reported their results in more than 50 patients and identified rectus abdominus and latissimus dorsi flaps as the most symmetric outcome. Of note, it would be of clinical interest to determine the correlation between 3D analysis and overall patient satisfaction, as well as those patients choosing breast-

Table 1
Clinical applications of 3D imaging

Clinical setting	Potential clinical applications
Implant breast reconstruction	Surface measurements
	Breast volume
	Volumetric distribution
	Postoperative symmetry (validate revision procedure)
	Implant size/shape
	Outlines surgical procedure
	Posterior projection of implant
	Postmastectomy residual breast volume
	Postoperative edema
	Implant migration/contracture
Autogenous (flap) breast reconstruction	Surface measurements
	Breast volume
	Volumetric distribution
	Postoperative symmetry (validate revision procedure)
	Outlines surgical procedure
	Postmastectomy residual breast volume
	Postoperative edema
Breast augmentation	Surface measurements
	Breast volume
	Volumetric distribution
	Preoperative asymmetry
	Implant size/shape
	Posterior projection of implant
	Postoperative edema
	Implant migration/retracture
Breast reduction	Surface measurements
	Breast volume
	Volumetric distribution
	Preoperative asymmetry
	Postoperative symmetry (validate revision procedure)
	Outlines surgical procedure
	Postoperative edema

conservation surgery and considering further reconstruction; these studies currently are underway by our group.

Three-dimensional images obtained during the extended postoperative period also are useful to reconstructive surgeons. In the case of implant reconstruction, this approach may help to identify implant migration or leakage. Furthermore, all types of breast reconstruction undergo redistribution of volume over time, but this has never been well defined. Three-dimensional imaging now offers a tool for comparing the long-term results of various breast reconstruction procedures, and hopefully will provide important data that ultimately will lead to improvements in technique.

Aesthetic breast surgery

Three-dimensional imaging technology may find clinical use in aesthetic breast surgery as well, including procedures such as breast augmentation (implant) and reduction mammoplasty (breast reduction). Breast augmentation with insertion of breast implants is one of the most commonly performed plastic surgery procedures today. More than 250,000 breast augmentation procedures were performed in the United States in the year 2004 (www.plasticsurgery.org). Preoperative 3D analysis could provide important criteria for the surgeon to base the size and shape of the breast implant. Most women show some degree of baseline breast asymmetry, and 3D volumetric analysis could help to determine such differences objectively. Differences in breast volume could be used to identify clinically significant asymmetry and thus scenarios in which a patient likely would benefit from placement of implants of different sizes. Moreover, various types of implants are available for augmentation. Critical analysis of the patient's preoperative shape, along with her desired breast size, could help surgeons better choose a favorable implant for a patient.

For patients undergoing breast-reduction surgery, preoperative 3D analysis also would highlight baseline breast asymmetry and provide objective measurements for surgical planning. Volumetric measurements would be especially useful to the surgeon in this setting because it would provide objective measurements for the surgeon on which to base surgical tissue resection (1 g of tissue is $\simeq$ 1 mL) (Figs. 2F and 2G). Three-dimensional imaging also may provide criteria for deciding the optimal type of reduction procedure (ie, medial pedicle, inferior pedicle, or superior pedicle). For instance, medial pedicle procedures traditionally have been performed in patients whose breasts are reduced less than 1,000 mL of tissue. This guideline has been based on estimates only, and 3D imaging may provide true objective measurements for surgical planning. The use of 3D images to assess patients in the postoperative period also would be useful for breast reductions. As noted earlier, this tool provides a means to assess postoperative symmetry, changes in volumetric distribution with time, and compare the various surgical techniques. A summary of these various clinical applications is provided in Table 1.

Conclusions

We believe 3D imaging can serve as a valuable tool for various types of breast surgery, including breast reconstruction with implant/tissue expanders, local flap reconstruction, free-flap reconstruction, breast augmentation, and breast-reduction surgery. In each of these clinical scenarios, 3D analysis provides volumetric data that is of unique value for surgical planning and postoperative analysis.

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