Three-Dimensional Surface Imaging in Plastic Surgery: Foundation, Practical Applications, and Beyond

Jessica B. Chang, B.S.
Kevin H. Small, M.D.
Mihye Choi, M.D.
Nolan S. Karp, M.D.

New York, N.Y.

Summary: Three-dimensional surface imaging has gained clinical acceptance in plastic and reconstructive surgery. In contrast to computed tomography/magnetic resonance imaging, three-dimensional surface imaging relies on triangulation in stereophotography to measure surface *x*, *y*, and *z* coordinates. This study reviews the past, present, and future directions of three-dimensional topographic imaging in plastic surgery. Historically, three-dimensional imaging technology was first used in a clinical setting in 1944 to diagnose orthodontologic conditions. Karlan established its use in the field of plastic surgery in 1979, analyzing contours and documenting facial asymmetries. Present use of three-dimensional surface imaging has focused on standardizing patient topographic measurements to enhance preoperative planning and to improve postoperative outcomes. Various measurements (e.g., volume, surface area, vector distance, curvature) have been applied to breast, body, and facial topography to augment patient analysis. Despite the rapid progression of the clinical applications of three-dimensional imaging, current use of this technology is focused on the *surgeon's* perspective and secondarily the *patient's* perspective. Advancements in patient simulation may improve patient-physician communication, education, and satisfaction. However, a communal database of three-dimensional surface images integrated with emerging three-dimensional printing and portable information technology will validate measurements and strengthen preoperative planning and postoperative outcomes. Three-dimensional surface imaging is a useful adjunct to plastic and reconstructive surgery practices and standardizes measurements to create objectivity in a subjective field. Key improvements in three-dimensional imaging technology may significantly enhance the quality of plastic and reconstructive surgery in the near future. (*Plast. Reconstr. Surg.* 135: 1295, 2015.)

Three-dimensional surface imaging has gained popularity in plastic and reconstructive surgery worldwide. Previously, the standard of patient assessment has been two-dimensional photography; however, this modality lacks shape and depth.[1] Flaws are inevitable when representing a three-dimensional structure in two-dimensional form. Other imaging tools such as computed tomography and magnetic resonance imaging have attempted to supplement these deficiencies; however, they poorly depict external soft tissues of the body, and they are time-consuming, invasive, and cost-prohibitive. Three-dimensional topographic imaging is a significant advancement from two-dimensional photographic assessment because this modality accounts for the three-dimensional nature of the human body. This clinical technology measures and analyzes surfaces along *x*, *y*, and *z* coordinates in three-dimensional space.[2]

From the Department of Plastic Surgery, New York University Medical Center; and the Division of Plastic Surgery, New York–Presbyterian Hospital/Weill Cornell Medical College.
Received for publication June 26, 2014; accepted August 26, 2014.

DOI: 10.1097/PRS.0000000000001221

Disclosure: *The authors have no financial interest to declare in relation to the content of this article. No funding was received for this work.*

A "Hot Topic Video" by Editor-in-Chief Rod J. Rohrich, M.D., accompanies this article. Go to PRSJournal.com and click on "Plastic Surgery Hot Topics" in the "Videos" tab to watch.

To overcome the deficiencies of conventional photography and radiographic imaging, various three-dimensional imaging modalities, including three-dimensional cephalometry, morpho-analysis, moiré topography, and three-dimensional ultrasonography, have been developed.[3] However, this review focuses on three-dimensional photogrammetry and its diverse application in plastic surgery. Three-dimensional photography uses triangulation, which overlays multiple images of the same object from different angles to form a three-dimensional image.[4] This article reviews the past, present, and future orientations of three-dimensional surface imaging in plastic surgery.

PAST

Although two-dimensional photography has recorded qualitative characteristics of the human body since the 1800s, three-dimensional surface imaging was first clinically applied in 1944; Thalmaan used stereophotogrammetry to capture the facial three-dimensional surface and diagnose orthodontologic conditions.[5,6] Soon after, Tanner and Weiner attempted to standardize three-dimensional photography by comparing anthropometric measurements to three-dimensional measurements.[7] Their efforts enabled Burke and Beard to apply a multiplex plotting system to analyze facial surface contours and track facial asymmetry over time.[8–11] In 1979, using moiré topography, Mitchell Karlan applied three-dimensional imaging to plastic surgery, particularly facial asymmetries that were difficult to analyze from plain photographs.[12] Of note, moiré topography superimposes contour maps from facial grids onto the object image and manually analyzes points by ruler and caliper.[13]

However, because incorporating contour mappings seemed tedious and costly, two other techniques, based on structured light or stereophotogrammetry, gained prominence. Although both rely on triangulation, stereophotography uses two cameras arranged as a stereo pair to provide points of intersection between disparate images and to allow for depth perception (Fig. 1, *left*). Corresponding raw images are matched in space to create a three-dimensional image that can be converted into a three-dimensional breast

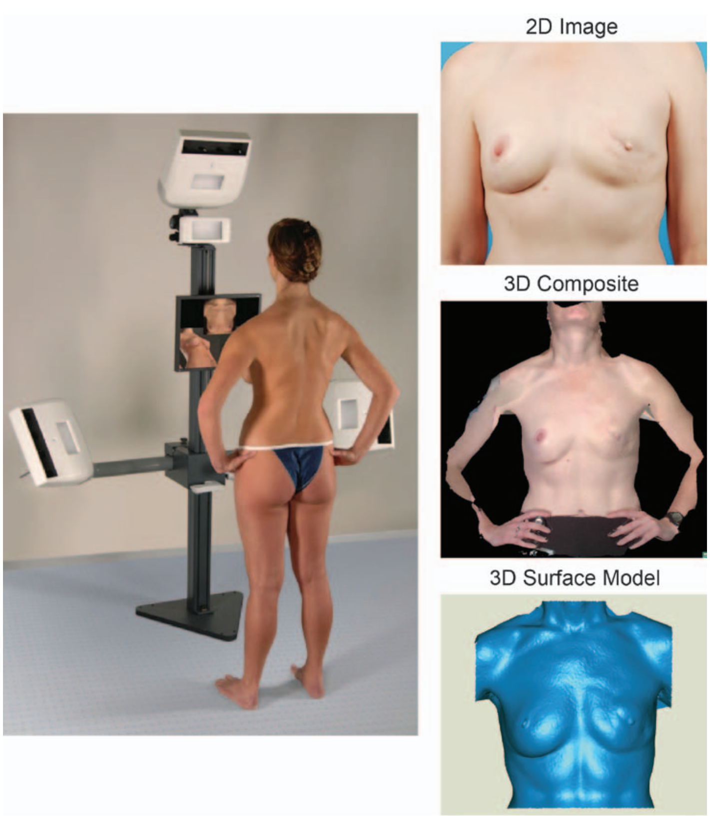

Fig. 1. (*Left*) Example of a three-dimensional imaging system (Canfield Imaging). (*Right*) Comparison of two-dimensional photograph, three-dimensional photography, and three-dimensional surface modeling using three-dimensional imaging software.

model using three-dimensional software (Fig. 1, *right*). Structured light uses a projector to shine a light pattern onto the targeted surface, which distorts and bends the light at an angle that is captured by a camera system and translated into three-dimensional coordinates.[14] Both techniques are currently used depending on the application, and have been refined over time.

With the continued maturation of accurate and precise three-dimensional imaging, clinical investigators began to extrapolate qualitative measurements from these photographs. In 1988, Cutting et al. developed software allowing three-dimensional images to be rotated to any angle, and distance measurements could be performed from specified point-to-point locations.[15] For the first time, this technology was used for postoperative analysis to examine craniofacial reconstruction. In the 1990s, three-dimensional photography and analysis continued its evolution; both Motoyoshi et al. and Ras et al. used different cameras at various angles to evaluate patients with facial asymmetry, cleft lip and palate, and concluded that it was valid and reliable.[16–20]

With this foundation at the beginning of the twenty-first century, various clinicians used three-dimensional imaging for facial analysis. Ferrario et al. evaluated cleft lip and palate three-dimensional postoperative photographs, suggesting additional procedures for improved cosmetic appearances.[21,22] Nkenke et al. analyzed the behavior of soft tissues of the face after patients underwent maxillary distraction osteogenesis for midfacial hypoplasia and found that their results were asymmetric.[23] By 2004, three-dimensional imaging had grown from measuring static Euclidian distances to measuring dynamic changes in soft-tissue positioning with facial expression,[24] growth, and development,[25,26] including the formation of wrinkles.[27] Nemoto et al. also studied the progression of wrinkles, suggesting corrective procedures based on three-dimensional photographic measurements (i.e., forehead lifts).[28]

In conjunction with applying three-dimensional imaging to the face, investigators have used three-dimensional photography for the breast. Initial breast studies using three-dimensional imaging (circa 2002 to 2003) evaluated factors affecting breast shape and symmetry.[29,30] Patients undergoing unilateral breast reconstruction received quantitative measurements of breast projection, volume, and contour to determine the expander and permanent implant size for symmetry.[29] However, the earliest prospective cohort study comparing outcomes of those who underwent preoperative and postoperative two-dimensional versus three-dimensional analysis found no significant difference in postoperative outcomes.[30] Of note, these analyses applied two-dimensional measurements to three-dimensional photographs, as there was no standardized approach to measure volumetric analysis and other three-dimensional parameters.

Three-dimensional technology has co-evolved with its clinical applications, and the systems in present use include the CAM3D (Erlargen, Germany), C3D (Beirut, Lebanon), Axis Three (Miami, Fla.), Canfield Scientific (Fairfield, N.J.), Crisalix (Lausanne, Switzerland), Di3D (Dimensional Imaging, Glasgow, Scotland), and 3dMDface (3dMD, Atlanta, Ga.) devices. CAM3D, C3D, and Axis Three rely on the structured-light technique; Canfield, Crisalix, and Di3D use stereophotogrammetry; and 3dMD combines both.[14,31] All systems vary in their camera setup; for example, CAM3D uses two cameras, whereas C3D uses two stereo pairs of cameras.[14] These systems also vary in colors, capture time, and computed tomographic image fusion capabilities.[31] Di3D adds time as a fourth dimension. Because three-dimensional surface imaging systems differ widely in technique and technology, selection is based on intended application.

PRESENT

Since 2005, use of three-dimensional surface imaging developed exponentially and has focused on standardized measurements of body topography and assessment of surgical outcomes. Whereas in the past, studies were based mainly on improving three-dimensional images, present-day studies have emphasized validating three-dimensional imaging.

Standardization of Breast and Body Surface Measurements

To enhance the utility of three-dimensional imaging, a standardized approach of creating and integrating three-dimensional measurements with three-dimensional images was required. Using the breast as a template (Fig. 2, *above*), Tepper et al. identified a reproducible technique to measure volume of an isolated anatomical structure.[32] They used three-dimensional software to define a patient-individualized chest wall template (Fig. 2, *center*) to measure volume and volumetric differences of each patient (Fig. 2, *below*).[33] This template was created by defining the boundaries of the breast: superiorly where the breast projects from the chest wall, laterally at the most lateral extent of the inframammary

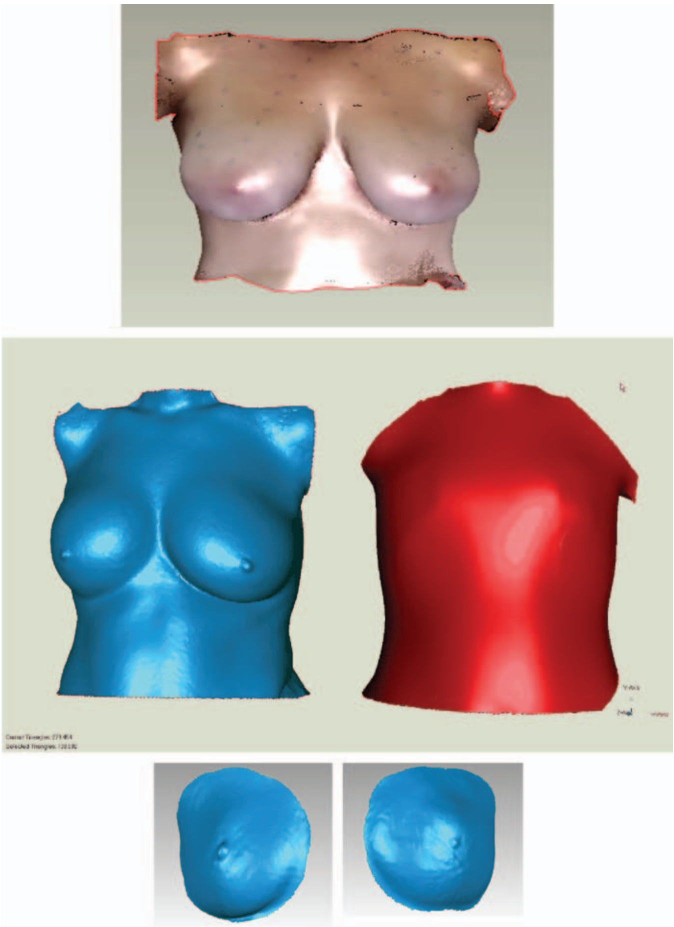

Fig. 2. Three-dimensional imaging of a sample patient's torso (*above*) alongside her individualized chest wall template (*center*). Each surface scan is aligned to a standardized chest wall to isolate a closed object so that volumetric analysis can be performed of each individual breast (*below*).

fold, medially at the most medial extent of the inframammary fold, and inferiorly at the lowest pole of the breast (Fig. 3).[32] Each surface scan is aligned to a standardized chest wall to isolate a closed object so that volumetric analysis can be performed of each individual breast (Fig. 2, *below*).[33] Furthermore, the imaging software could generate surface area and vector measurements of breast contour and size (Fig. 3).[32,34] The technology-driven approach to breast imaging and analysis correlated with standard manual linear measurements and magnetic resonance imaging volumes.[35] These images and the associated analysis were proven accurate and reproducible.[32] With evidence-based analytical tools to assess three-dimensional breast imaging, the technique could now be applied to various anatomical topographies.

The development of accurate and reproducible three-dimensional imaging and analysis has led to the creation of an initial database to assess morphologic differences in patients (specifically, craniofacial asymmetries). Kau et al. have analyzed adults and children using facial templates, which are constructed from soft-tissue averages obtained from three-dimensional images.[36] With these facial templates, 80 adults and 72 children with craniofacial anomalies were compared, determining morphologic differences with the ultimate utility of advanced surgical planning.[36,37] Of note, this novel concept of three-dimensional databases has small numbers and needs thousands of patients to generate conclusions; however, data from this type of collection could revolutionize outcomes in plastic surgery.

Three-dimensional imaging has been used to not only identify deviations from average but also analyze facial changes over time. By comparing two-dimensional photographs taken at two different intervals in time, Lambros[38] stipulated the mechanics of facial aging and provided a

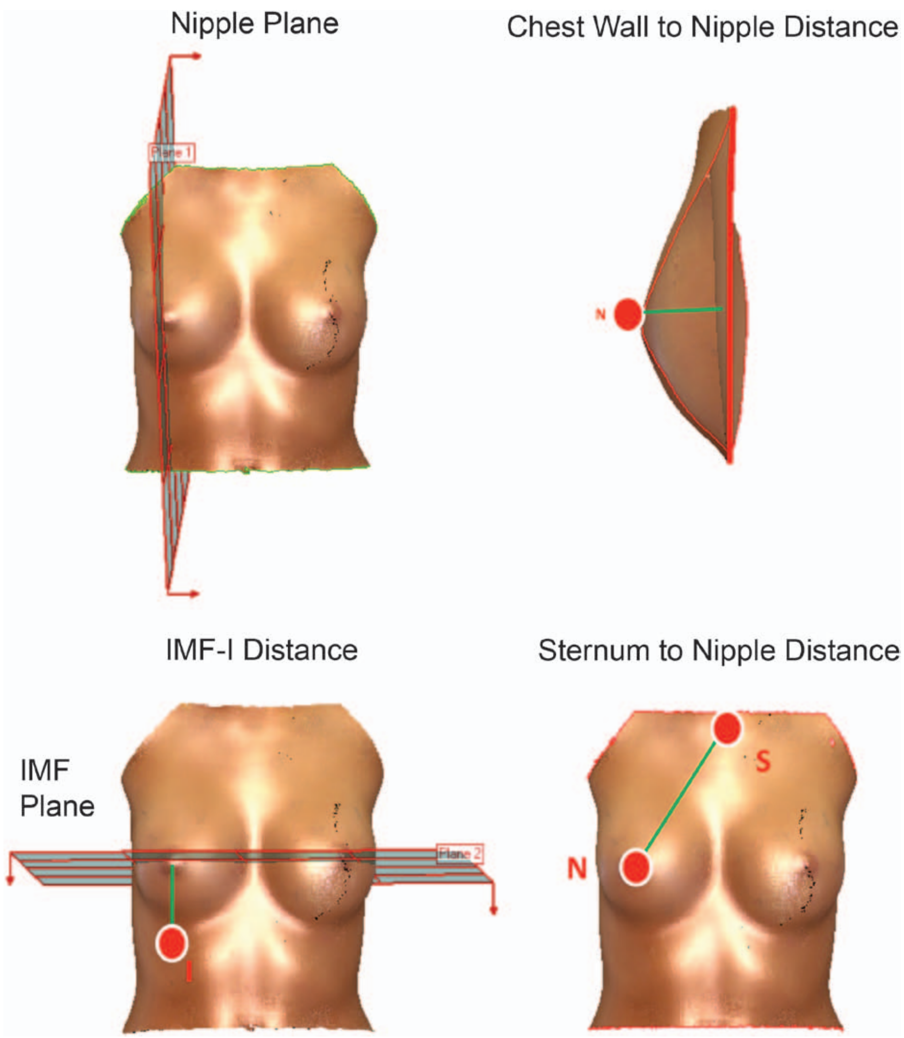

Fig. 3. Three-dimensional imaging can be used to define various planes [nipple plane (*above*, *left*) and inframammary fold plane (*below*, *left*)] and reproducible distances [chest wall–to-nipple distance (*above*, *right*) and sternal notch–to-nipple distance (*below*, *right*)]. *IMF*, inframammary fold.

foundation for further three-dimensional imaging and analysis. His findings of centralization of the upper lid arc with age, for example, are corroborated by the three-dimensional animations of Iblher et al., who measured soft tissue of female faces in two different age groups and depicted increased displacement and surface stretching in the elderly population.[39] Facial growth, traditionally measured by lateral cephalographs based on two-dimensional landmarks, can now be quantified by means of superimposition of serially captured three-dimensional facial photographs.[14] The improved ability to make accurate static and dynamic measurements of facial surfaces has provided an objective science in a subjective field. Again, this concept of database collection is in its infancy and needs patients from all demographics for scientific impact.

Improvement of Postoperative Outcomes

With a foundation of accurate and reproducible three-dimensional measurements, surgeons have applied this analysis to breast cases and documented postoperative outcomes.[40] For example, when shapes of breast implants were studied for impact on breast mound, round implants were found to provide less breast projection than anatomical implants.[41] Another study documented that long-term postoperative anteroposterior projection after implant placement was less than predicted.[40] Three-dimensional imaging also enabled monitoring of retention associated with autologous fat transfer; results indicated that fat retention was both volume- and time-dependent.[42] Advancements in three-dimensional imaging may eventually provide a blueprint outlining the amount of fat to harvest for optimal graft survival. As more clinical studies emerge, three-dimensional outcomes may influence future surgical techniques.

Postoperative analysis has also been applied to the face. Following surgical correction of facial asymmetry, three-dimensional images confirmed that soft-tissue topography correlated with skeletal changes.[43] In addition, postrhinoplasty imaging of unilateral cleft patients demonstrated measurably improved alar symmetry, increased tip projection, and reduced nasolabial angle.[44] Long-term durability of hyaluronic acid–based fillers for facial rejuvenation has been also substantiated by means of three-dimensional imaging.[45] Analysis from facial three-dimensional imaging augments the missing soft-tissue measurements from cephalometrics, and ultimately may enhance surgical technique as we continue to critically evaluate postoperative outcomes with objective three-dimensional measurements.

Three-dimensional imaging not only has provided a way to assess postoperative outcomes but also has become a powerful aid in preoperative planning. The prospective study by Tepper et al. found that three-dimensional imaging offered valuable volumetric data that helped guide tissue expander–based breast reconstruction, including initial size of tissue expander, total volume of expansion, and final implant size/shape.[46] In this study, patient satisfaction and breast symmetry significantly increased with the application of three-dimensional imaging. Furthermore, the prospective survey of patients receiving three-dimensional photography reported by Donfrancesco et al. concluded that three-dimensional imaging positively impacted the entire breast augmentation process, and patients strongly preferred a center with three-dimensional imaging technology.[47]

Three-dimensional imaging has been equally efficacious in assessing noninvasive/minimally invasive treatments for various plastic surgical conditions. Volumetric measurement of infantile hemangioma enabled the rapid, accurate, and noninvasive characterization of propranolol on the volume of the vascular anomalies.[48] In another study, use of three-dimensional photography to monitor treatment of infants with deformational plagiocephaly with an orthotic helmet device has proven to be instrumental in assessing volumetric and morphologic changes over time.[49] Three-dimensional measurements of wounds, particularly severe pressure ulcers, have also been standardized and validated; three-dimensional imaging proved successful for monitoring static and improving wounds for wound perimeter, volume, depth, and length.[50] Three-dimensional imaging and its associated measurements may be a beneficial analytical tool for both invasive and noninvasive outcomes alike.

FUTURE

Although the clinical applications of three-dimensional surface imaging have progressed rapidly over the past decade, limitations include cost, ease-of-use, patient applicability, and others. Over time, the pricing and efficiency of the equipment will become more agreeable; however, the imaging and analysis must transition from the surgeon's perspective to the patient's perspective to be truly applicable to the patient's surgical experience. By integrating the technology in the surgical consultation, both the patient and the surgeon can appreciate the preoperative anatomical canvas and proposed surgical corrections, thus improving patient-physician communication, patient education, and patient satisfaction.

Preoperative Planning and Outcome Simulation

Clinicians have recently integrated three-dimensional computed tomographic models with three-dimensional stereophotogrammetry to create accurate, photorealistic illustrations of facial topography and enable preoperative planning in procedures such as rhinoplasty.[51,52] The merging of these modalities enhances the precision of the surgical simulation. Another possible adjunct to improved patient consultation is the integration of surgical simulation and three-dimensional imaging systems. In breast surgery, patients may select the size and width of their implants but are unable to visualize how different implants would affect their outcomes.

Creasman et al. documented that breast augmentation patients felt that their three-dimensional preoperative simulation consultations were essential in helping them select their surgeon and believed the simulations to accurately predict the postoperative results.[53] Not only could patients visualize their simulated outcome (Fig. 4), they could also compare this simulation to their true postoperative results at follow-up visits. In a follow-up questionnaire, the majority of respondents indicated that three-dimensional imaging was the "main reason" or was "very important" in helping them select their surgeon and believed the simulation to be accurate.

The potential success of three-dimensional simulation in breast surgery should encourage investigators to create and apply the same

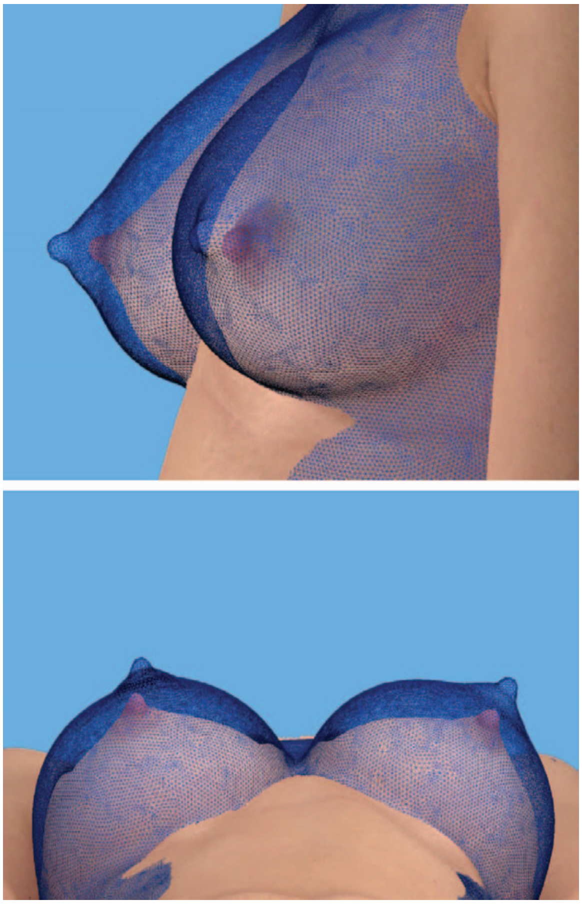

Fig. 4. Demonstration of surgical simulation using three-dimensional software for breast augmentation with round silicone implants.

principles to other procedures (e.g., rhinoplasty, rhytidectomy, otoplasty). Of note, surgical simulations are only estimates of postoperative results based on the collaboration of engineers and plastic surgeons, and the software lacks evidence-based data (i.e., the impact of age, body mass index, ethnicity, and sex on surgical outcomes). Ultimately, with these factors integrated, outcome simulations will improve patient consultation and enhance preoperative planning.

Creation of Central Imaging Database and Integration of Fourth Dimension (Time)

To accurately simulate patient outcomes based on scientific data, a communal database of preoperative and postoperative three-dimensional images is necessary. Such a database would allow the software engineers to construct surgical simulations based on scientific fact instead of predictions. Thus, surgeons would be able to simulate surgical results based on patient demographics, comorbid conditions, and operative details over various time points (fourth dimension). Incorporating time allows investigators to create a database to review outcomes and make informed conclusions. Studies have observed trends in soft-tissue stretch after mammaplasty, such as volume loss and lower pole elongation, and the effect of age on soft-tissue mobility of the lower face.[35,39] However, these studies lack the contributions of sex, race, weight, and others. Quan et al., in four-dimensional studies, have shown that breast reductions are stable 1 year after operation, but further and larger studies are needed to influence accurate surgical simulation and outcomes.[54] Extrapolating data from a central database of postoperative outcomes from various procedures with various comorbidities could vastly improve the quality of outcome simulation. With surgical simulation, there will be an inherent improvement in preoperative planning and prediction of outcomes.

Integrating Three-Dimensional Imaging with Portable Information Technology

Integration of three-dimensional imaging with portable information technology would provide easily accessible digital images and improve patient-surgeon communication. The utility of Google Glass (Google, Mountain View, Calif.), a wearable computer with an optical head-mounted display and touchpad camera, in a surgical practice for hands-free photographic and video documentation has been established.[55] The merging of Google Glass and three-dimensional imaging can create hands-free photography in the operating room or enable downloading of the patient's virtual picture with associated measurements during the operation. Unforeseen circumstances in the operating room, such as variable anatomy or patient positioning, could be integrated with three-dimensional preexisting images and data analysis; this merger between preoperative consultation and intraoperative experience may decrease operative time and optimize surgical results. Furthermore, three-dimensional software available on the portable tablet or even the smartphone, such as the Apple iPad or iPhone (Apple Corp., Cupertino, Calif.), may provide similar benefits. Patients now would have a digital file of their images, data analysis, and surgical simulation that can help guide decision-making and become a part of their medical record, to be shared with the remainder of their provider team.

Individualizing Patient Treatment

Similarly, the contemporary advent of three-dimensional printing has proven extremely useful in the medical field, producing custom jaw implants,[56] upper extremity prostheses,[57] cranioplasty implants,[58] and others. These customized implants ensure that required components provide an exact fit and maximize the early return of function. Integration of three-dimensional imaging and printing may further pave the way for custom-made implants and prostheses, reducing operative time and improving patient satisfaction. Custom devices made according to the preoperative data could revolutionize the world of implants in plastic surgery, providing a perfect fit for the available skin envelope or achieving symmetry with the contralateral side. Similarly, three-dimensional imaging could be a required screening by our armed forces; in traumatic amputations, rather than relying on the contralateral hand for comparison, hand and finger prostheses could be rapidly customized based on preexisting stored images that provide manufacturers with the precise topography of the preamputation hand.

Limitations

Despite the progress of three-dimensional imaging and its impact on plastic surgery, several limitations of the imaging systems and the associated software currently prevent its integration into the standard approach to reconstructive and aesthetic surgical procedures. Three-dimensional surface-imaging systems vary with regard to cost, capture and processing speed, interface portability, image quality, and special features (e.g., fourth dimension, computed tomographic data compatibility). A comparative analysis of popular imaging systems emphasized that interested providers should define their requirements before deciding which system to purchase.[31] Because an individual unit can cost from $20,000 to $100,000, cost-benefit analyses should be performed to determine the cost-effectiveness of purchasing these instruments. Furthermore, systems and software analysis may be vastly operator dependent. Advancements must be made in the imaging software to be more user friendly, efficient, and accurate to engage the utility of plastic surgeons.

System utility also depends on body habitus, skin tone, and timing. The quality of imaging is not ideal for morbidly obese women or those with dark complexions because of shadowing interference. Furthermore, early postoperative analysis may not be accurate; postoperative inflammatory edema or fibrosis of the subcutaneous tissue distorts three-dimensional images and associated analysis.[59] Therefore, postoperative results should be defined for up to 1 year after surgery, mimicking the same standard as two-dimensional photography. Moreover, to generate a three-dimensional image database for data-driven surgical simulations, years of data are required from various surgeons representing all patient demographics to truly depict an accurate operative portrayal.

CONCLUSIONS

Three-dimensional surface imaging is a useful adjunct to clinical plastic and reconstructive surgery practices; this technology aids in preoperative planning and analysis, improves postoperative results, reduces costs and operative time, and standardizes measurements to create objectivity in an otherwise subjective field. Future abilities to predict or simulate surgical outcomes over time may enhance patient-provider communication and patient education, conversion-to-surgery rates, and satisfaction. Between improvement in key features of current technology, integration with portable information technology, and the realistic potential of individualizing patient treatment with custom-made devices, three-dimensional surface imaging may significantly benefit the quality of reconstructive and aesthetic surgery in the near future.

Nolan S. Karp, M.D.
305 East 47th Street, Suite 1A
New York, N.Y. 10017
nolan.karp@nyumc.org

REFERENCES

1. Da Silveira AC, Daw JL Jr, Kusnoto B, Evans C, Cohen M. Craniofacial applications of three-dimensional laser surface scanning. *J Craniofac Surg.* 2003;14:449–456.
2. Geng J. Structured-light 3D surface imaging: A tutorial. *Adv Opt Photonics* 2011;3:128–160.
3. Honrado CP, Larrabee WF Jr. Update in three-dimensional imaging in facial plastic surgery. *Curr Opin Otolaryngol Head Neck Surg.* 2004;12:327–331.
4. Halazonetis DJ. Acquisition of 3-dimensional shapes from images. *Am J Orthod Dentofacial Orthop.* 2001;119:556–560.
5. Tzou CH, Frey M. Evolution of 3D surface imaging systems in facial plastic surgery. *Facial Plast Surg Clin North Am.* 2011;19:591–602, vii.
6. Thalmaan D. *Die Stereogrammetrie: ein diagnostisches Hilfsmittel in der Kieferorthopaedie (Stereophotogrammetry: A Diagnostic Device in Orthodontology).* Zurich, Switzerland: University of Zurich; 1944.
7. Tanner JM, Weiner JS. The reliability of the photogrammetric method of anthropometry, with a description of a miniature camera technique. *Am J Phys Anthropol.* 1949;7:145–186.
8. Burke PH, Beard FH. Stereophotogrammetry of the face: A preliminary investigation into the accuracy of a simplified system evolved for contour mapping by photography. *Am J Orthod.* 1967;53:769–782.
9. Beard LF, Burke PH. Evolution of a system of stereophotogrammetry for the study of facial morphology. *Med Biol Illus.* 1967;17:20–25.

10. Burke P. Serial stereophotogrammetric measurements of the soft tissues of the face: A case of a girl with mild facial asymmetry from 3 weeks to 10 years of age. *Br Dent J.* 1983;155:373–379.
11. Burke P. Four-dimensional facial change. *Br J Orthod.* 1984;11:170–184.
12. Karlan MS. Contour analysis in plastic and reconstructive surgery. *Arch Otolaryngol.* 1979;105:670–679.
13. Hajeer MY, Ayoub AF, Millett DT, Bock M, Siebert JP. Three-dimensional imaging in orthognathic surgery: The clinical application of a new method. *Int J Adult Orthodon Orthognath Surg.* 2002;17:318–330.
14. Kau CH, Richmond S, Incrapera A, English J, Xia JJ. Three-dimensional surface acquisition systems for the study of facial morphology and their application to maxillofacial surgery. *Int J Med Robot.* 2007;3:97–110.
15. Cutting CB, McCarthy JG, Karron DB. Three-dimensional input of body surface data using a laser light scanner. *Ann Plast Surg.* 1988;21:38–45.
16. Motoyoshi M, Namura S, Arai HY. A three-dimensional measuring system for the human face using three-directional photography. *Am J Orthod Dentofacial Orthop.* 1992;101:431–440.
17. Ras F, Habets LL, van Ginkel FC, Prahl-Andersen B. Method for quantifying facial asymmetry in three dimensions using stereophotogrammetry. *Angle Orthod.* 1995;65:233–239.
18. Ras F, Habets LL, van Ginkel FC, Prahl-Andersen B. Quantification of facial morphology using stereophotogrammetry: Demonstration of a new concept. *J Dent.* 1996;24:369–374.
19. Ras F, Habets LL, van Ginkel FC, Prahl-Andersen B. Longitudinal study on three-dimensional changes of facial asymmetry in children between 4 to 12 years of age with unilateral cleft lip and palate. *Cleft Palate Craniofac J.* 1995;32:463–468.
20. Ayoub A, Garrahy A, Hood C, et al. Validation of a vision-based, three-dimensional facial imaging system. *Cleft Palate Craniofac J.* 2003;40:523–529.
21. Ferrario VF, Sforza C, Dellavia C, Vizzotto L, Carù A. Three-dimensional nasal morphology in cleft lip and palate operated adult patients. *Ann Plast Surg.* 2003;51:390–397.
22. Ferrario VF, Sforza C, Tartaglia GM, Sozzi D, Carù A. Three-dimensional lip morphometry in adults operated on for cleft lip and palate. *Plast Reconstr Surg.* 2003;111:2149–2156.
23. Nkenke E, Langer A, Laboureux X, et al. Validation of in vivo assessment of facial soft-tissue volume changes and clinical application in midfacial distraction: A technical report. *Plast Reconstr Surg.* 2003;112:367–380.
24. Okada E. Three-dimensional facial simulations and measurements: Changes of facial contour and units associated with facial expression. *J Craniofac Surg.* 2001;12:167–174.
25. Ferrario VF, Sforza C, Serrao G, Ciusa V, Dellavia C. Growth and aging of facial soft tissues: A computerized three-dimensional mesh diagram analysis. *Clin Anat.* 2003;16:420–433.
26. Nute SJ, Moss JP. Three-dimensional facial growth studied by optical surface scanning. *J Orthod.* 2000;27:31–38.
27. Akazaki S, Nakagawa H, Kazama H, et al. Age-related changes in skin wrinkles assessed by a novel three-dimensional morphometric analysis. *Br J Dermatol.* 2002;147:689–695.
28. Nemoto M, Uchinuma E, Yamashina S. Three-dimensional analysis of forehead wrinkles. *Aesthetic Plast Surg.* 2002;26:10–16.
29. Galdino GM, Nahabedian M, Chiaramonte M, Geng JZ, Klatsky S, Manson P. Clinical applications of three-dimensional photography in breast surgery. *Plast Reconstr Surg.* 2002;110:58–70.
30. Nahabedian MY, Galdino G. Symmetrical breast reconstruction: Is there a role for three-dimensional digital photography? *Plast Reconstr Surg.* 2003;112:1582–1590.
31. Tzou CH, Artner NM, Pona I, et al. Comparison of three-dimensional surface-imaging systems. *J Plast Reconstr Aesthet Surg.* 2014;67:489–497.
32. Tepper OM, Unger JG, Small KH, et al. Mammometrics: The standardization of aesthetic and reconstructive breast surgery. *Plast Reconstr Surg.* 2010;125:393–400.
33. Tepper OM, Small K, Rudolph L, Choi M, Karp N. Virtual 3-dimensional modeling as a valuable adjunct to aesthetic and reconstructive breast surgery. *Am J Surg.* 2006;192:548–551.
34. Liu C, Luan J, Mu L, Ji K. The role of three-dimensional scanning technique in evaluation of breast asymmetry in breast augmentation: A 100-case study. *Plast Reconstr Surg.* 2010;126:2125–2132.
35. Creasman CN, Mordaunt D, Liolios T, Chiu C, Gabriel A, Maxwell GP. Four-dimensional breast imaging, part I: Introduction of a technology-driven, evidence-based approach to breast augmentation planning. *Aesthet Surg J.* 2011;31:914–924.
36. Kau CH, Zhurov A, Richmond S, Cronin A, Savio C, Mallorie C. Facial templates: A new perspective in three dimensions. *Orthod Craniofac Res.* 2006;9:10–17.
37. Kau CH, Zhurov A, Richmond S, et al. The 3-dimensional construction of the average 11-year-old child face: A clinical evaluation and application. *J Oral Maxillofac Surg.* 2006;64:1086–1092.
38. Lambros V. Observations on periorbital and midface aging. *Plast Reconstr Surg.* 2007;120:1367–1376; discussion 1377.
39. Iblher N, Gladilin E, Stark BG. Soft-tissue mobility of the lower face depending on positional changes and age: A three-dimensional morphometric surface analysis. *Plast Reconstr Surg.* 2013;131:372–381.
40. Tepper OM, Small KH, Unger JG, et al. 3D analysis of breast augmentation defines operative changes and their relationship to implant dimensions. *Ann Plast Surg.* 2009;62:570–575.
41. Kovacs L, Eder M, Zimmermann A, et al. Three-dimensional evaluation of breast augmentation and the influence of anatomic and round implants on operative breast shape changes. *Aesthetic Plast Surg.* 2012;36:879–887.
42. Choi M, Small K, Levovitz C, Lee C, Fadl A, Karp NS. The volumetric analysis of fat graft survival in breast reconstruction. *Plast Reconstr Surg.* 2013;131:185–191.
43. Christou T, Kau CH, Waite PD, Kheir NA, Mouritsen D. Modified method of analysis for surgical correction of facial asymmetry. *Ann Maxillofac Surg.* 2013;3:185–191.
44. Dixon TK, Caughlin BP, Munaretto N, Toriumi DM. Three-dimensional evaluation of unilateral cleft rhinoplasty results. *Facial Plast Surg.* 2013;29:106–115.
45. Donath AS, Glasgold RA, Meier J, Glasgold MJ. Quantitative evaluation of volume augmentation in the tear trough with a hyaluronic acid-based filler: A three-dimensional analysis. *Plast Reconstr Surg.* 2010;125:1515–1522.
46. Tepper OM, Karp NS, Small K, et al. Three-dimensional imaging provides valuable clinical data to aid in unilateral tissue expander-implant breast reconstruction. *Breast J.* 2008;14:543–550.
47. Donfrancesco A, Montemurro P, Hedén P. Three-dimensional simulated images in breast augmentation surgery: An investigation of patients' satisfaction and the correlation between prediction and actual outcome. *Plast Reconstr Surg.* 2013;132:810–822.
48. Hermans DJ, Maal TJ, Bergé SJ, van der Vleuten CJ. Three-dimensional stereophotogrammetry: A novel method in volumetric measurement of infantile hemangioma. *Pediatr Dermatol.* 2014;31:118–122.
49. Moghaddam MB, Brown TM, Clausen A, DaSilva T, Ho E, Forrest CR. Outcome analysis after helmet therapy using 3D photogrammetry in patients with deformational plagiocephaly:

The role of root mean square. *J Plast Reconstr Aesthet Surg.* 2014;67:159–165.

50. Davis AJ, Nishimura J, Seton J, Goodman BL, Ho CH, Bogie KM. Repeatability and clinical utility in stereophotogrammetric measurements of wounds. *J Wound Care* 2013;22:90–92, 94.
51. Xin P, Yu H, Cheng H, Shen S, Shen SG. Image fusion in craniofacial virtual reality modeling based on CT and 3dMD photogrammetry. *J Craniofac Surg.* 2013;24:1573–1576.
52. Moscatiello F, Herrero Jover J, González Ballester MA, Carreño Hernández E, Piombino P, Califano L. Preoperative digital three-dimensional planning for rhinoplasty. *Aesthetic Plast Surg.* 2010;34:232–238.
53. Creasman CN, Mordaunt D, Liolios T, Chiu C, Gabriel A, Maxwell GP. Four-dimensional breast imaging, part II: Clinical implementation and validation of a computer imaging system for breast augmentation planning. *Aesthet Surg J.* 2011;31:925–938.
54. Quan M, Fadl A, Small K, et al. Defining pseudoptosis (bottoming out) 3 years after short-scar medial pedicle breast reduction. *Aesthetic Plast Surg.* 2011;35:357–364.
55. Muensterer OJ, Lacher M, Zoeller C, Bronstein M, Kübler J. Google Glass in pediatric surgery: An exploratory study. *Int J Surg.* 2014;12:281–289.
56. World première UHasselt: First 3D-printed lower jaw implant. Hasselt University. Available at: http://www.uhasselt.be/UH/Tijdschriften/ToonPersmededeling.html?i=482. Accessed February 2, 2012.
57. Not Impossible Labs. Not Impossible's "Project Daniel" uses 3D printers to make prosthetic arms for children of war in South Sudan. Available at: http://www.notimpossiblelabs.com/#!project-daniel/c1imu. Accessed December 27, 2013.
58. 3D-printed Skull Implanted in Patient. UMC Utrecht. Available at: http://www.umcutrecht.nl/research/news/2014/03/3d-printed-skull-implanted-in-patient.htm. Accessed March 27, 2014
59. Pallara T, Signoretti M, Cagli B, Cogliandro A, Marangi GF, Persichetti P. The volumetric analysis of fat graft survival in breast reconstruction. *Plast Reconstr Surg.* 2013;132:668e–669e.