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The Use of a 3D Simulator Software and 3D Printed Biomodels to Aid Autologous Breast Reconstruction

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Abstract Aesthetically pleasing and symmetrical breasts are the goal of reconstructive breast surgery. However, multiple procedures are sometimes needed to improve a reconstructed breast's symmetry and appearance. Since all breasts vary in terms of volume, height, width, projection, orientation, and shape, the lack of attention to these details at the moment of flap shaping in autologous reconstruction can lead to poor results. Recent advances in 3-dimensional (3D) surface imaging and printing technologies have allowed for improvement in autologous breast reconstruction symmetry. While 3D printing technology is becoming faster, more accurate, and less expensive, the technology required to obtain proper 3D breast images remains expensive, including laser scanners or 3D photogrammetric cameras. In this study, we present a novel use of an aesthetic surgery simulator software as an affordable alternative to obtaining 3D breast images and creating 3D printed biomodels to aid in the precise shaping of the flap. This approach aims to optimize aesthetic results in autologous breast reconstruction avoiding surgical revisions and reducing surgical times.
Level of Evidence IV This journal requires that authors assign a level of evidence to each article. For a full description of these Evidence-Based Medicine ratings, please refer to the Table of Contents or the online Instructions to Authors www.springer.com/00266.

Keywords Biomodels · Breast mold · Simulation software · 3D imaging · 3D printing · Breast reconstruction · Flap shaping

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Introduction

The application of computer-aided design and manufacturing (CAD/CAM) techniques in plastic surgery has steadily grown in recent years. Current areas of application include bone and craniofacial surgery, upper extremity and hand surgery, nasal and auricular cartilage reconstruction and skin substitutes among others [1, 2]. CAD/CAM techniques can generate CAD-compatible virtual models by using computed tomographic (CT) or magnetic resonance imaging (MRI) data, which can be then printed as physical solid models known as biomodels. These models are exact replicas of internal organs or structures (such as bones and the heart) or external organs (such as the breast). The advantages of its use are summarized in Table 1.

While CT or MRI data are typically used to generate biomodels of internal organs or structures, these data, although suitable for volumetric breast planning, are unsuitable for morphologic breast planning. A CT study is carried out with the patient in the supine decubitus position, while an MRI study is carried out with the patient in the prone decubitus position. Both decubiti alter the breast shape, making those images unsuitable for morphologic planning. To obtain adequate breast imaging for the generation of a biomodel, scans must be performed in a standing position, and such technologies as laser scanning or stereophotogrammetry are usually required for this

Table 1 Advantages of using biomodels

Allows accurate measurements
Allows surgical simulation on the model itself
Visualize problems prior surgery
Time saving during surgery
Provides confidence during surgery
Facilitates surgical procedures and reducing risks
Development of medical devices

purpose. Notwithstanding, these technologies are costly and require large equipment to be placed in spacious rooms.

Aesthetically pleasing and symmetrical breasts are the goal of reconstructive breast surgery. However, multiple procedures are sometimes needed to improve a reconstructed breast's symmetry and appearance. Since all breasts vary in terms of volume, height, width, projection, orientation, and shape, the lack of attention to these details at the moment of flap shaping in autologous reconstruction can lead to poor results (Fig. 1). In this scenario, the use of 3D-printed breast biomodels or custom molds helps in the precise shaping of the flap, providing an opportunity to improve autologous breast reconstruction symmetry and avoid multiple procedures.

In this study, we present a novel use for 3D aesthetic surgery simulator software as an affordable alternative to obtaining 3D images and customizing printed breast molds for autologous breast reconstruction.

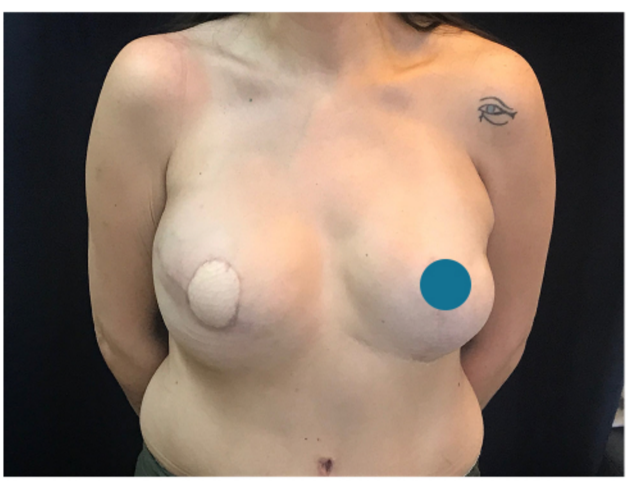

Fig. 1 Anterior postoperative view of a 45-year old patient reconstructed with an abdominal-based flap where the lack of attention to the volume, height, width, projection, orientation, and shape of the contralateral breast at the moment of flap shaping led to a poor result

Methods

The use of biomodels is indicated in patients undergoing autologous breast reconstruction in whom the flap can be modeled using a mold. Although the main indication is delayed unilateral cases of autologous breast reconstruction where the patient does not need or wish to modify the contralateral breast, it can also be indicated in immediate cases of reconstruction. The main characteristics of candidates for this method are summarized in Table 2.

Image Acquisition

The scanning of the breast is usually scheduled 1 week before the procedure. 3D surface images of the breast are acquired with the 3D simulation technology Crisalix™ (Virtual Aesthetics, Crisalix, Lausanne, Switzerland), which uses a web-based software and a portable 3D sensor plugged into a tablet. This technology has the advantage of being portable and available online. Scanning is carried out with the patient in a standing position while slightly spreading her arms and breathing normally (Fig. 2) [See Video 1, which shows the scanning of the breast]. Once the torso is completely scanned, which usually take few seconds, a 3D model of the remaining contralateral breast is rendered and mirrored, obtaining a simulation of the resulting reconstruction (Fig. 3) [See Video 2, which shows the mirroring of the contralateral breast]. It is important to note that the result of this simulation is not used as a prediction of surgical results and it is not shown to the patient. It is only used to generate the custom breast mold. The advantages of 3D planning for autologous breast reconstruction are summarized in Table 3.

Biomodel Design

Once the rendered breast image is ready, it is exported for edition and design of the personalized breast mold (Mirai3D, Buenos Aires, Argentina); (Fig. 4). First, the selected breast boundaries are set because they will

Table 2 Candidates for breast biomodels

Autologous reconstruction
Appropriate donor site volume
Unilateral breast reconstruction
Satisfying shape of the remaining breast
Delayed breast reconstruction
No willingness to modify the contralateral breast
Asymmetric immediate breast reconstruction
Immediate bilateral cases

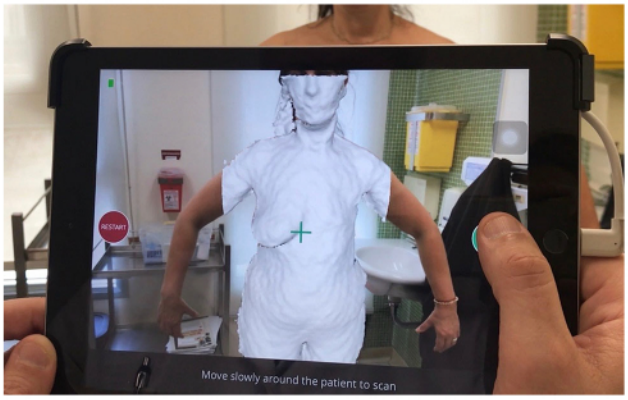

Fig. 2 A simulator software is used for 3D breast surface imaging with the patient in a standing position while slightly spreading her arms and breathing normally

influence the size and shape of the breast mold. We employ a set of five breast boundaries as proposed by Wesselius [3]. These include a lateral boundary set by the midaxillary line, a superolateral boundary defined by the transition of the pectoral muscle curve into the breast curvature, an upper boundary located at the height of the second rib, a medial boundary set by the sternomanubrial joint, and a lower boundary defined by the inframammary fold. It is important to note that this lower boundary sometimes cannot be properly imaged in large or highly ptotic breasts, generating inaccurate breast scanning in these cases [4]. Once the boundaries of the mold are set, a nipple areolar complex is designed to resemble a breast, and multiple fenestrations are incorporated to allow the visualization of the skin through the mold (Fig. 5). Because the creation of fenestrations increases the fragility of the biomodel, a peripheral reinforcement and thickening is applied at the level of its borders.

Table 3 Advantages of 3D planning in autologous breast reconstruction

Standing position
Both volumetric and morphologic planning
Generation of biomodels or custom molds
Quick, exact and reliable
Easy to use

Biomodel Fabrication

Once the virtual model is ready, it is exported to a 3D printer to create a biomodel by fused deposition modeling (FDM), which is the most widely used 3D printing technology. The biomodel is created by selectively depositing melted material layer-by-layer in a predetermined path with very fast turnaround times (Fig. 6). The materials used are filaments of polylactic acid (PLA), which is a biodegradable thermoplastic polymer that melts when heated and then returns to a solid state upon cooling. By using a 3D printer of special dimensions (Ultimaker 3 Extended^{TM}, Ultimaker, Geldermalsen, The Netherlands), the full printing process takes around 12 to 14 h [See Video 3, which shows the printing of the breast biomodel].

Biomodel-Assisted Autologous Reconstruction

The custom 3D breast mold created using PLA can be sterilized in plasma or ethylene oxide and used at the operating table during the surgery (Fig. 7). The breast mold is used to determine the required flap volume and to shape the breast mound in terms of height, width, projection, and orientation. It is important to note that the biomodel can be

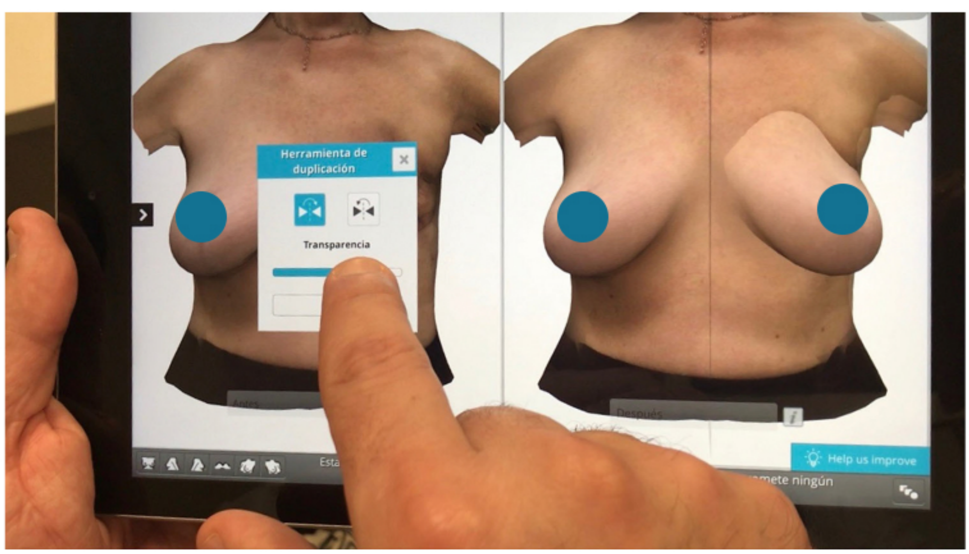

Fig. 3 The remaining contralateral breast is rendered and mirrored, obtaining a simulation of the resulting reconstruction

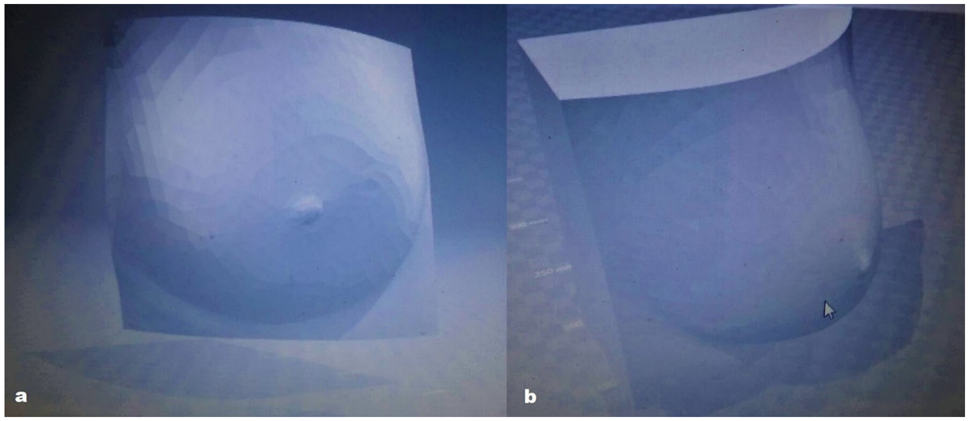

Fig. 4 The rendered breast image is exported for edition and design of the biomodel; **a** frontal view; **b** oblique view

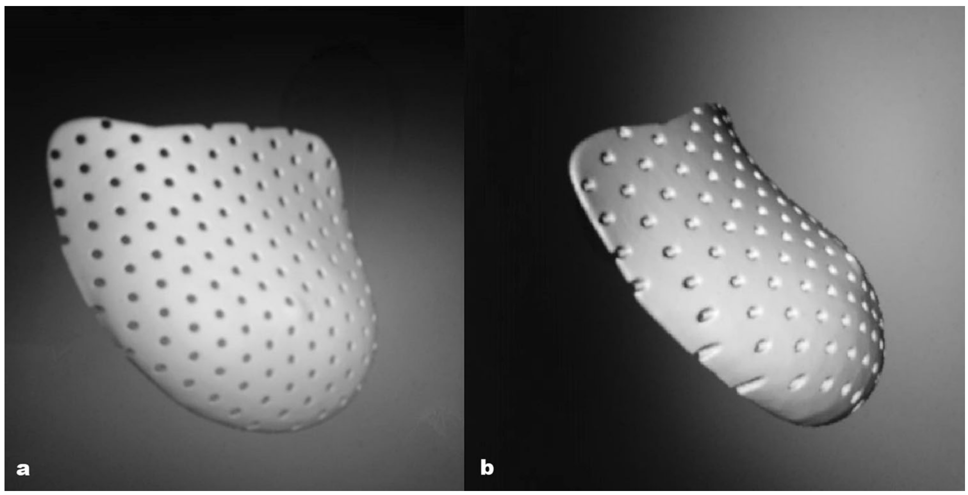

Fig. 5 The biomodel incorporates a nipple, to resemble a breast, and multiple fenestrations, to allow the visualization of the skin through the mold; **a** frontal view; **b** lateral view

Fig. 6 The biomodel is created by selectively depositing melted PLA layer-by-layer in a predetermined path

Fig. 7 The custom 3D breast mold is sterilized in plasma or ethylene oxide and is used to shape the flap at the same operating table during the surgery

used to shape all types of flaps typically employed in breast reconstruction, which is especially useful for less experienced surgeons.[See Video 4, which shows the intraoperative flap shaping assisted by the biomodel].

Representative Case

A 59-year-old patient diagnosed with infiltrating ductal carcinoma of the right breast in 2010 underwent breast-conserving surgery along with chemotherapy and radiotherapy. Due to a relapse of the disease, she was treated 1 year later at another facility, which included a mastectomy and direct-to-implant breast reconstruction with an implant that was too small followed by contralateral beast reduction. After 8 postoperative years, she presented with capsular contracture and augmentation of the contralateral breast due to weight gain. Because she declined an operation on her contralateral breast, which was considered of satisfying shape, we offered her an abdominally based autologous breast reconstruction with a TRAM flap and the use of breast molds to optimize results. The procedure was carried out in less time due to a faster flap-shaping process, and the result was considered highly satisfactory for both surgeon and patient. The full sequence of this representative case, showing preoperative, perioperative and postoperative photographs, to demonstrate the versatility of the method in abdominal flap-based breast reconstruction, is presented in Fig. 8a–f.

We also conducted a telephone-based survey to measure patient's impressions on the process of image acquisition and their overall satisfaction with the surgery. Patient's impressions on the process of image acquisition were graded as A, B or C where A was quick and simple, B mildly complex and C time consuming and complex. Patients' satisfaction with the procedure and final result were rated on a scale of 1 to 5, where 1 was poor, 2 was fair, 3 was good, 4 was very good, and 5 was excellent.

During the follow-up carried out by telephone, all patients were reached, and four patients rated the procedure and final results as excellent and one patient as very good. For all patients, the process of image acquisition was quick and simple.

Discussion

Breast reconstruction is perhaps the more aesthetic of all reconstructive procedures. Only plastic surgeons specializing in breast reconstruction know that all breasts are different, and their reconstruction requires insight, skill, and experience. Although 3D planning has been used for several years in implant-based breast reconstruction to choose an appropriate expander implant size/shape, guide the amount of expansion, identify the need for a symmetry procedure, and facilitate postoperative objective assessment [5], its use in autologous breast reconstruction has been less popular. There are only three previous reports in the medical literature regarding the use of 3D imaging to generate customized breast molds to aid in the shaping of the flap [6–8]. All of these studies used various methods for 3D breast surface imaging, such as stereoscopic photography or laser scanning, which are expensive and

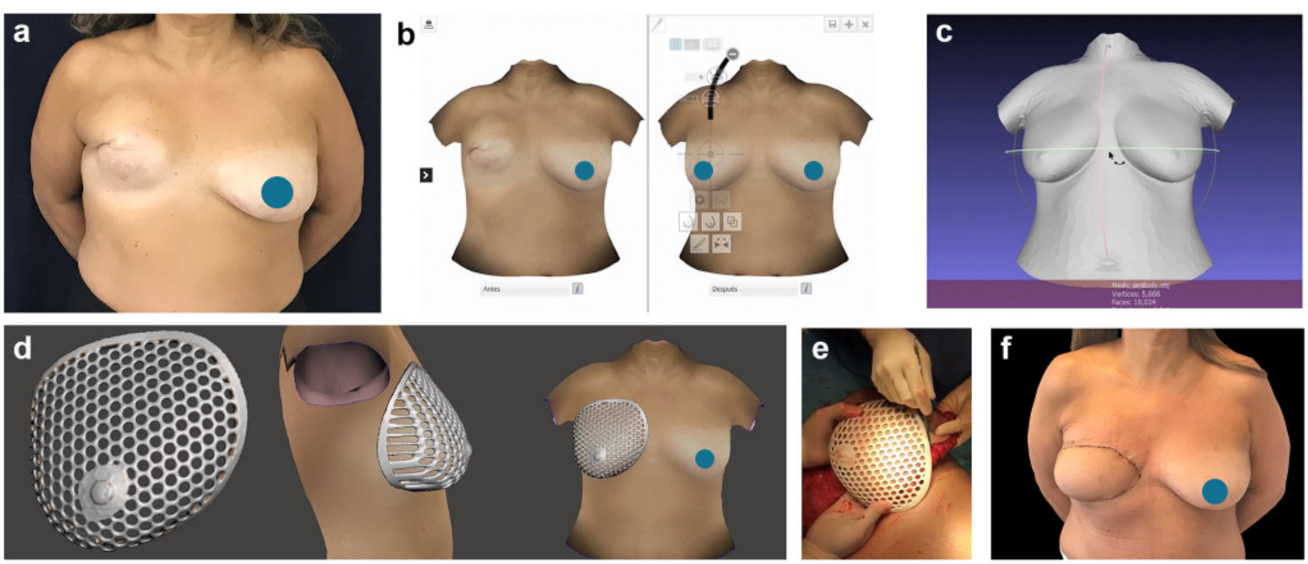

Fig. 8 **a** Anterior preoperative view of a 59-year-old patient reconstructed whit an abdominal-based flap and the use of breast molds to optimize results; **b** the remaining contralateral breast is rendered and mirrored; **c** the rendered breast image is exported for edition; **d** design of the biomodel; **e** the biomodel is used to shaping the flap intraoperatively; and **f** anterior postoperative view of the same patient at 45 days

inconvenient technologies for most plastic surgeons specializing in breast reconstruction. These technologies also require significant resources, including equipment, training, and office space. The high cost and lack of access has prevented the use of 3D scanning in wider clinical applications.

Crisalix is a simulator software designed for use in aesthetic plastic surgery. It is user-friendly and offers 3D-simulated images of breast augmentation outcomes. It helps a surgeon decide which implant to use along with the volume and shape required to achieve the desired result [9]. It requires only a tablet with a portable 3D sensor to plug in. Although popular among plastic surgeons for aesthetic purposes, its use in breast reconstructions has never been reported. With an annual subscription cost ranging from USD $1,761 to $6,082 [10], it is indeed a practical and affordable alternative to the more expensive technologies required to generate custom breast molds. Moreover, 3D printing technology continues to become faster, more accurate, and cheaper. The cost of 3D printers and the PLA material used to print the biomodels is also affordable. The estimated price of PLA per kg is USD $22.99, while the total cost of production of our biomodel is USD $100. The use of this biomodel in autologous reconstruction, which is particularly useful in the novice's hands, reduces or avoids the need for surgical revisions of both the reconstructed and contralateral breast, which translates into an effective reduction in health expenditures. This is particularly important in countries such as ours where surgeries for symmetrization of the contralateral breast are not covered by the public health system or private insurance companies, which results in the cost being paid by the patient.

All previously reported custom breast molds have been solid and were used after being wrapped in sterile plastic bags [6–8]. For accurate shaping of the flap, we consider it important to visualize the skin through fenestrations, and we therefore incorporated this feature into the design phase. The PLA employed in the printing of the mold also allowed sterilization using ethylene oxide or plasma. The mold can therefore be used at the operating table during surgery avoiding the risk of infectious complications. Considering that fat necrosis leading to a reduction in the final breast volume is one of the most common complications of autologous breast reconstruction [11], the virtual model could also be edited to create a breast mold slightly bigger while maintaining the proper shape.

3D biomodels have been also reported for other uses in autologous breast reconstruction. 3D models of the deep inferior epigastric perforator (DIEP) system are useful for rapid harvest of DIEP flaps, which also provides the precise location of the relevant perforator exit point and intramuscular course to streamline the intramuscular dissection of DIEP flaps [12, 13]. The 3D image of the breast can also be digitally processed and by adding tetrahedral meshes, it can be used to create customized scaffolds that provide adequate mechanical protection to allow for adipogenesis and angiogenesis when associated with fat grafting [14]. New lines of research also include endowing scaffolds with the capability for loading and sustained release of drugs to prevent postsurgical complications, such as doxorubicin or cefazolin [15]. Thus, these 3D custom porous scaffolds for breast tissue engineering offer a promising future for breast reconstruction surgeries with no donor site morbidity and incorporated novel therapeutic capabilities.

Conclusions

Although originally conceived for aesthetic purposes, the use of 3D aesthetic surgery simulator software is an affordable alternative to the expensive technology currently used to generate customized molds for autologous breast reconstruction. The use of these biomodels facilitates breast shaping, especially in the novice's hands, which reduces surgical times and avoids surgical revisions.

Further studies including larger samples and comparing satisfaction rates between patients reconstructed with autologous options using and not using 3D planning and breast biomodels are warranted.

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Compliance with Ethical Standards

Conflict of interest The author declares that he has no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. For this type of study formal consent is not required.

Informed Consent Patient provided written informed consent for publication. Additional consent was provided for the use of their images.

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