

Preoperative breast volume evaluation of one-stage immediate breast reconstruction using three-dimensional surface imaging and a printed mold

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Abstract

Background: Accurate assessment of breast volume is an essential component of preoperative planning in one-stage immediate breast reconstruction (IBR) for achieving breast symmetry and a satisfactory cosmetic outcome. In this study, we compared breast volume estimation using three-dimensional (3D) surface imaging with magnetic resonance imaging (MRI) to determine the accuracy of breast volume measurements. Further, a 3D printing mold for facilitating autologous breast reconstruction intraoperatively is described.

Methods: Patients scheduled to therapeutic or prophylactic mastectomy with one-stage IBR, either by autologous tissue transfer or direct implant, from 2016 to 2019, were enrolled in this study. 3D surface image and MRI were performed to evaluate breast volume and shape. The results were validated by the water displacement volume of the mastectomy specimen. Finally, a 3D printing mold was designed for breast reconstruction with autologous tissue.

Results: Nineteen women who were scheduled to have 20 mastectomies (18 unilateral and one bilateral) were included. There was a strong linear association between breast volume measured using the two different methods and water displacement of mastectomy specimens when a Pearson correlation was used (3D surface image: $r = 0.925$, $p < 0.001$; MRI: $r = 0.915$, $p < 0.001$). Bland-Altman plots demonstrated no proportional bias between the assessment methods. The coefficient of variation was 52.7% for 3D surface imaging and 59.9% for MRI. The volume of six breasts was evaluated by both measurements and the intraclass correlation coefficient was 0.689 for 3D surface image ($p = 0.043$) and 0.743 for MRI ($p = 0.028$).

Conclusion: Using 3D surface image to evaluate breast shape and volume is a quick, effective, and convenient method. The accuracy, reproducibility, and reliability of 3D surface imaging were comparable with MRI in our study. In addition, 3D-printed molds can achieve better symmetry and aesthetic outcomes in immediate autologous breast reconstructions.

Keywords: 3D printing; 3D surface image; Immediate breast reconstruction; MRI; Volumetric analysis

1. INTRODUCTION

With increased patient awareness and cancer screening, more patients are being diagnosed with early breast cancer. Some patients prefer immediate breast reconstruction (IBR), which improves psychological well-being and quality of life.¹ It has

been shown that neoadjuvant chemotherapy does not influence the occurrence of IBR-related complications² and that IBR does not postpone the start of adjuvant therapy. Comparing implant-based reconstruction with postmastectomy radiotherapy (PMRT), autologous reconstruction with PMRT results in better quality of life and sensory recovery, fewer complications, and lower failure rate.^{3,4}

Accurate breast volume assessment is an essential component of preoperative planning in both reconstructive and aesthetic breast surgery for achieving breast symmetry and satisfactory outcomes. Breast shape is dynamic, highly dependent on patient position, and highly variable between patients; therefore, any objective method of volumetric analysis requires versatility.

Since the earliest report of breast volume measurement by Bouman,⁵ various techniques, such as water volume displacement,⁶ negative molding using thermoplastic casts,⁷ direct anthropomorphic measurements,⁸ indirect anthropomorphic measurements using two-dimensional (2D) imaging or three-dimensional (3D) imaging, and 3D surface scanning technology,

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have been described with varying accuracy and reliability. Although magnetic resonance imaging (MRI) demonstrated the highest accuracy,⁹ 3D surface scanning has been gaining popularity due to its convenience and low cost. Currently, there is no consensus on how to estimate breast volume accurately.

In one-stage autologous IBR, neo-breast 3D shaping and orientation are crucial.¹⁰ A mirror image of the contralateral breast is an ideal template to achieve natural contour and breast symmetry in unilateral breast reconstruction. Estimation of the breast volume before surgery might help achieve this. In addition, this knowledge may lead to shorter surgery time and fewer secondary corrective procedures. In this study, we aimed to compare breast volume estimation using a 3D surface scanner and MRI to determine the accuracy of breast volume measurements. The results were validated by the water volume displacement of the mastectomy specimen. Further, the usefulness of a 3D-printed mold constructed from the mirror image of the contralateral breast to facilitate autologous IBR is discussed.

2. METHODS

2.1. Participant recruitment and data collection

This was a prospective cohort study. The study sample was recruited from breast tumors patients treated at the Department of Plastic Surgery and Comprehensive Breast Health Center at the Taipei Veterans General Hospital, who were scheduled to undergo mastectomy and one-stage IBR, either by autologous tissue transfer or direct implant, from 2016 to 2019. 3D surface scanning and MRI were performed within one month before the reconstruction surgery. There were no surgical procedures between MRI or 3D scan and surgery, and thus, breast volume remained unchanged. Patients with available preoperative imaging data (either MRI or 3D scan) and water volume

displacement were included. The demographic features, preoperative calculated data, water volume displacement data, and pre and postoperative photographs were collected. The medical ethical committee of the Taipei Veterans General Hospital approved this study, and all subjects gave written informed consent for the use of their data.

2.2. Acquisition of the 3D surface image

3D surface scanning and mold fabrication were performed—the patient was naked in a standing position. The breast was palpated and marked with tape to define boundaries by a plastic surgeon (C.J. Feng); usually, the superior boundary is located at the second intercostal space, the medial boundary is located at the lateral sternal line, the inferior border is located at the inframammary fold, and the lateral border is located at the anterior axillary line. A handheld Eva scanner was used for 3D surface imaging (Fig. 1A, Artec 3D, Luxemburg). An experienced technician scanned the breast territory while the patient was instructed to maintain a relaxed standing position.

2.3. Breast volume calculation

After 3D surface data were acquired, the breast shape was reconstructed using postprocessing software (Fig. 1B, Artec Studio 12 Professional x64 12.1.6.16, Artec 3D, Luxemburg), which took about 30 minutes. Since the chest wall contour could not be detected by the scanner, it was assumed to be a flat plane. Then, breast volume was calculated using Meshmixer software version 3.4.35 (Fig. 1C).

For MRI images, we used the Slicer4 version 4.11.0 software to reconstruct the 3D image and calculate breast volume. Slice thickness was usually 0.8 to 1.2 mm. A region of interest encompassing the breast tissue was then segmented from individual slices. The posterior border of the breast was considered as the pectoralis

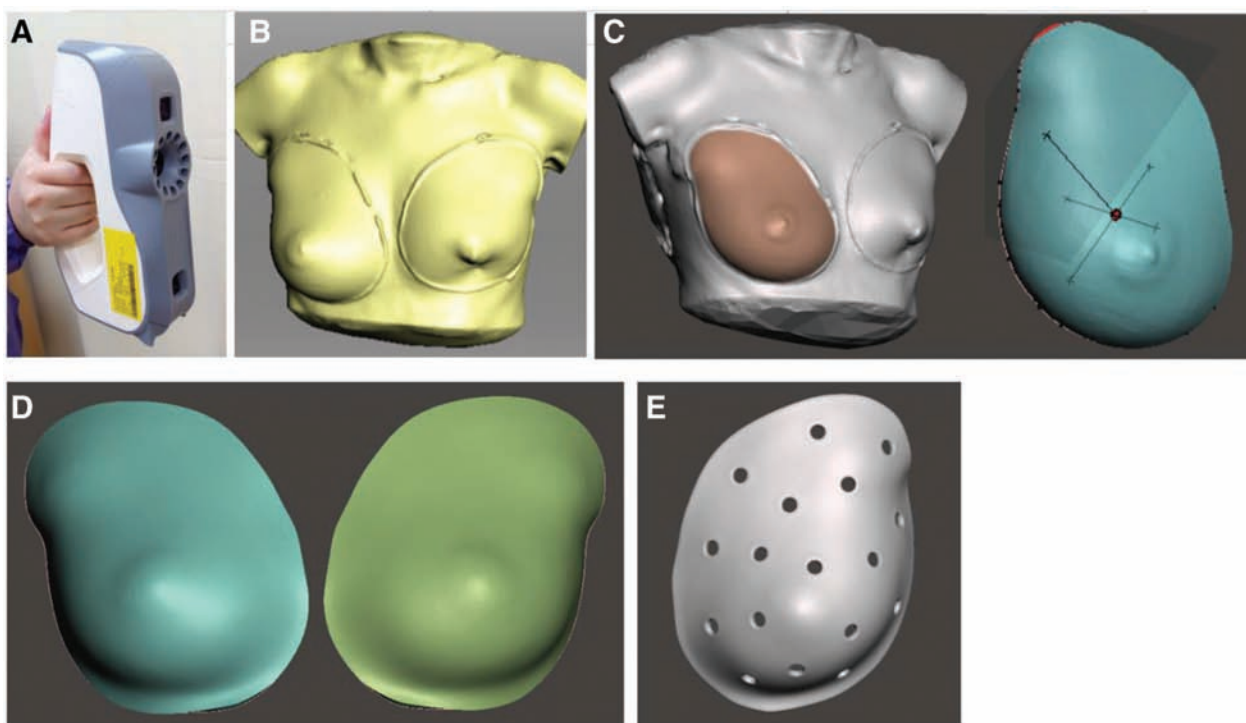


Fig. 1 Steps of 3D scanning and mold fabrication: A, Surgeons and technicians scanned the breast territory using a handheld 3D scanner (Artec 3D Eva); B, 3D image was obtained using postprocessing software (Artec Studio 12 Professional x64 12.1.6.16); C, Contralateral breast volume and mirror image were obtained from contralateral breast to ensure a symmetrical and natural reconstruction and for mold design (Meshmixer [3.4.35]); D, Mirrored breast mold design; E, After image drilling, the mold was 3D-printed (CR10) and prepared using plasma sterilization. This mold facilitated flap inset intraoperatively. 3D, three-dimensional.

major fascia. Given that all slices had equal thickness, the sum of all segmented volumes indicated the total breast volume.

2.4. Mastectomy specimen and autologous flap volume

The mastectomy specimen volume was measured using water volume displacement: a customized metal water tank was prepared in the operating room and filled with saline. A drain hole was located on the lateral side of the tank. The excised breast specimen was put inside the tank, and the volume of drained water was considered as the volume of the mastectomy specimen. The breast volume calculated from the 3D surface imaging or MRI was compared with the water volume displacement of the mastectomy specimen. After harvesting the autologous flap for breast reconstruction, water volume displacement was also used for volume measurement.

2.5. 3D-printed mold development

The 3D-printed mold was designed by Meshmixer version 3.4.35 software. A mirror image of the contralateral breast was constructed to achieve a natural and symmetric bilateral appearance in unilateral breast reconstruction (Fig. 1D). Image slicing (UltimakerCura 3.0.3) was performed before 3D printing. A 3D printer (CR-10s, Creality, China) printed the mold with polylactic acid (PLA) material (160g weight); this step took 15 to 20 hours (Fig. 1E). The mold was sterilized using a plasma sterilization technique. The mold, designed from the mirror image of the contralateral breast, facilitated the orientation and shaping of the neo-breast with autologous flap intraoperatively. On the basis of the neo-breast and flap target volume, excess tissue was discarded and trimmed. To assure breast symmetry and natural contour, the operating table was bent to place the patient in a sitting position while the flap was inset.

2.6. Statistical analysis

All analyses were performed using SPSS 23.0 software (IBM Corp., Armonk, NY). Pearson correlation was performed to assess the degree of association between breast volume estimation using the two methods (3D surface imaging or MRI) and water displacement, and linear regression was used to define the relation between the two methods and water displacement. Subsequently, linear regression models were also used to develop volume-predicting formulae. To assess the agreement between the two methods, a Bland-Altman plot was used to determine relationships between the magnitude of bias and degree of variation.¹¹ A one-sample *t* test was used to determine the mean difference between the two measures. The SD was multiplied by 1.96 and added or subtracted to the mean difference to establish the upper and lower limits of the confidence interval, respectively. A 95% limit of agreement was used to determine bias. To evaluate reproducibility, a coefficient of variation (CV = 100 SD/mean) was calculated and expressed as a percentage of mean breast volume. To choose the most reliable boundary definition, the intraclass correlation coefficient (ICC) was also calculated.¹² A value of *p* < 0.05 was considered statistically significant.

3. RESULTS

3.1. Study cohort

Nineteen female patients who were scheduled to undergo 20 mastectomies (18 unilateral and one bilateral) were included in this study. Eighteen mastectomies were performed for malignancy, whereas one for prophylaxis and the other for benign breast tumor. Of the mastectomies performed, nipple-sparing mastectomy was performed in 10 breasts (50%) and non-nipple-sparing mastectomy was performed in 10 breasts (50%). Before mastectomy, 3D surface images were available for 14 (70%)

Table

Demographic features of the study cohort

	Study cohort (N = 19)
Unilateral mastectomy, n (%)	18 (94.7%)
Bilateral mastectomy, n (%)	1 (5.3%)
Contralateral prophylactic mastectomy, n (%)	1 (5.3%)
Total mastectomy specimens, n	20
Nipple-sparing mastectomy, n (%)	10 (50%)
Non-nipple-sparing mastectomy, n (%)	10 (50%)
Breast volume estimation	20
3D surface image	14 (70%)
MRI	12 (60%)
Both	6 (30%)
Immediate breast reconstruction	20
Autologous tissue transfer	14 (70%)
Direct to implant	6 (30%)
Median age, years (range)	46 (33-64)
Mean BMI, kg/m ² (range)	23.3 (18.7-33.3)
Histology, n (%)	20
Invasive ductal	14 (70%)
Ductal carcinoma in situ	3 (15%)
Others	3 (15%)
Mean tumor size, cm (range)	1.8 (0-7)
Node positive, n (%)	7/20 (35%)
Neoadjuvant chemotherapy	7/19 (36.8%)
Breast cancer clinical stage, n (%)	18
DCIS	3 (16.7%)
1A	5 (27.8%)
IIA	5 (27.8%)
IIIB	3 (16.7%)
IIIC	2 (11.1%)

3D = three-dimensional; BMI = body mass index; DCIS = ductal carcinoma in situ; MRI = magnetic resonance imaging.

breasts, MRI was available for 12 (60%) breasts, and both measurements were available for six (30%) breasts. Regarding the one-stage IBR procedure, autologous tissue transfer was performed in 14 (70%) breasts, all using deep inferior epigastric perforator (DIEP) flaps, and direct implant was performed in six (30%) breasts. The median age of the patients was 46 years (range, 33-64 years), and the mean body mass index (BMI) was 23.3 kg/m² (range, 18.7-33.3 kg/m²). Complete pathological data were also available for all patients (Table).

3.2. Accuracy, reproducibility, and reliability of volume estimation

The mean mastectomy volume in the 3D surface imaging and MRI groups was 411.5 ± 275 mL and 438.4 ± 254.4 mL, respectively. There was no significant difference between the two groups. There was a strong linear association between the breast volumes measured using the two different methods and water volume displacement of mastectomy specimens as shown by the Pearson correlation coefficient (3D surface image: *r* = 0.925, *p* < 0.001; MRI: *r* = 0.915, *p* < 0.001). The mastectomy mean volume was defined by the following equation: mastectomy mean volume = (3D scan mean volume × 1.03) – 70.68 (Fig. 2A) or (MRI mean volume × 0.7) + 50.15 (Fig. 2B). The intersection point of both lines on the graph reflects the offset between the 3D-scanned and mastectomy specimen volumes, with the 3D scan method slightly overestimating the breast volume. This led to the inclusion of the figure 70.68 in the formula. The multiplication fact 1.03 shows that the slope of the graph is virtually 45°.

The volume calculation error of 3D surface image did not differ from 0 in terms of absolute volume (in milliliters): 56.6 ± 104.8 mL (*p* = 0.064). However, MRI systematically

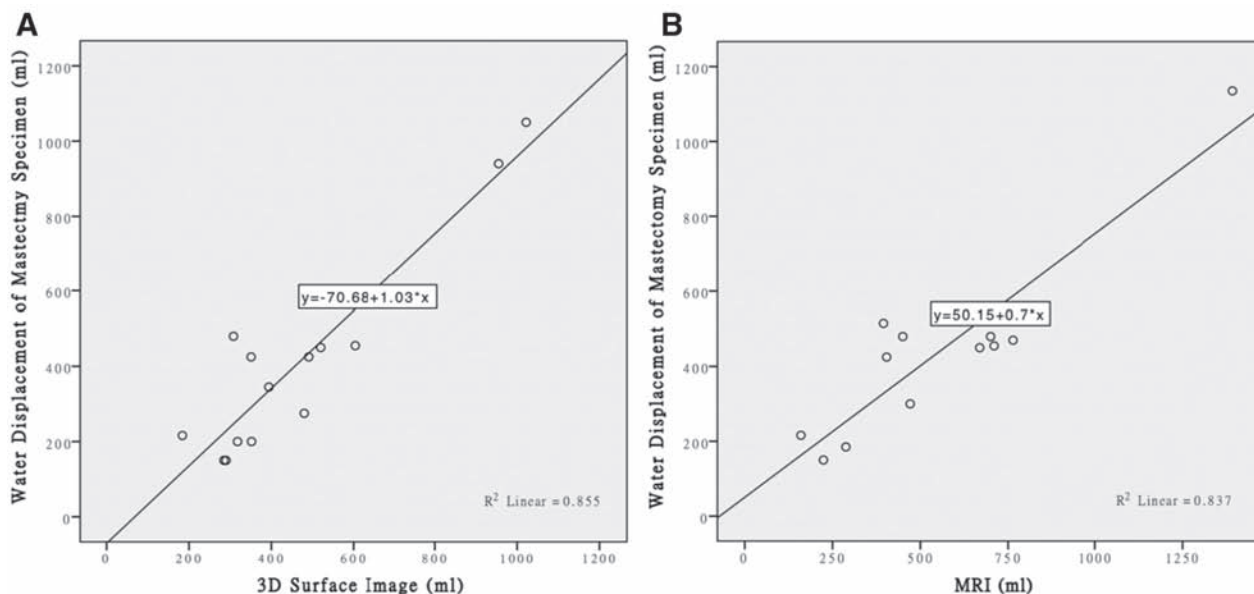


Fig. 2 A, Pearson correlation between breast 3D surface images and mastectomy specimen volumes ($r = 0.925$, $r^2 = 0.855$; $p < 0.001$); B, Pearson correlation between breast MRI and mastectomy specimen volumes ($r = 0.915$, $r^2 = 0.837$; $p < 0.001$). 3D, three-dimensional; MRI, magnetic resonance imaging.

overestimated the breast volume (mean, 113.8 ± 142.2 mL and $p = 0.018$). The Bland-Altman plots are shown in Fig. 3 and demonstrated no proportional bias between assessment methods.

The CV was 52.7% for 3D surface image and 59.9% for MRI. The volume of six breasts was evaluated by both measurements before mastectomy and the ICC was 0.689 for 3D surface image ($p = 0.043$) and 0.743 for MRI ($p = 0.028$).

In the 14 DIEP flap reconstructions performed, a 3D-printing mold was used in nine cases. We demonstrate a one-stage IBR case using preoperative volume estimation by 3D surface scan and 3D printing mold here. A 48-year-old woman had left breast invasive ductal carcinoma 3 years ago and underwent neoadjuvant chemotherapy, lumpectomy, and radiotherapy. After treatment, asymmetry, deformity, and nipple-areola complex retraction were found in her left breast. At this time,

she was diagnosed with local recurrence on the left breast. Nipple-sparing mastectomy and sentinel lymph node biopsy were planned. After comprehensive discussion, she decided to receive autologous breast reconstruction with a DIEP flap. We used 3D surface imaging to evaluate the bilateral breast volume and shape preoperatively in a standing position (Fig. 4A, B). According to the 3D surface imaging data, we calculated the volume of the healthy breast and a 3D printing mold was designed. The mold was sterilized before operation. During the operation, the excess tissue of the DIEP flap was removed on the basis of the calculated volume (Fig. 4C); neo-breast orientation and shaping were also facilitated by the mold (Fig. 4D). Since the intended volume and shape were determined according to the healthy breast, symmetry and natural contour were expected after neo-breast reconstruction. A good aesthetic outcome was achieved postoperatively (Fig. 4E).

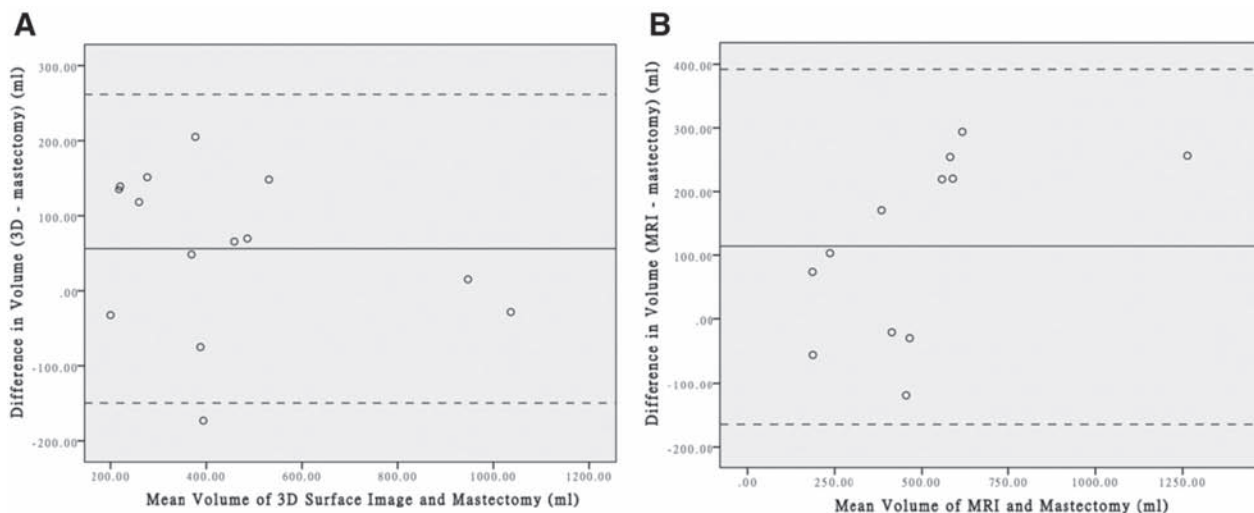


Fig. 3 A, Bland-Altman plot showing the difference in breast volume determined by 3D surface imaging and of the mastectomy specimen; B, Bland-Altman plot showing the difference in breast volume determined by MRI and of the mastectomy specimen. Solid lines represent the mean difference in volume and dotted lines represent the limits of agreement. 3D, three-dimensional; MRI, magnetic resonance imaging.



Fig. 4 An immediate autologous breast reconstruction case using 3D surface scanning and 3D-printed mold: A, Deformity and asymmetry of the left breast and asymmetry were noted preoperatively; B, Breast territory was marked with 3M tape for the 3D surface scan; C, 3D-printed mold facilitated DIEP flap inset; D, Fitting the flap to the mold after volume adjustment; E, Postoperative day 7 in sitting position, based on the mirror image of the healthy breast. Symmetry and natural contour were achieved. 3D, three-dimensional; DIEP, deep inferior epigastric perforator.

Another 52-year-old breast cancer patient (Fig. 5A) was diagnosed of right breast invasive ductal carcinoma, she underwent nipple-sparing mastectomy and DIEP reconstruction using 3D surface scan and printed mold. Estimation volume by 3D surface scan of healthy-side breast was 454 mL, and mastectomy side was 491 mL. Water displacement measurement of mastectomy specimen was 425 mL. DIEP flap was harvested with 550 mL, 102 mL was discarded after 3D printed mold assisted inset, and final implanted flap volume was 448 mL. Follow-up in 2 months after the operation, aesthetic outcome was achieved (Fig. 5B).

The third case is a 32-year-old woman with phyllodes tumor. The huge phyllodes tumor was difficult to estimate volume regarding reconstruction. We used the same method combining 3D surface scan and printed mold to perform IBR with satisfactory outcome (Fig. 6A, B) (3D estimation volume of right breast: 712 mL, left breast: 955 mL; water displacement measurement of left mastectomy specimen: 940 mL; final implanted flap volume: 805 mL).

4. DISCUSSION

We introduced an effective method of breast volume estimation by 3D surface scan and mold printing for one-stage immediate autologous breast reconstruction.

Immediate autologous breast reconstruction is a time-consuming procedure. A prolonged operation time is associated with the risk of complications and reoperation.¹³ Reconstruction should begin once mastectomy is completed. Predesigned breast shaping reduces operative time and prevents further symmetrization procedures.¹⁰ For young plastic surgeons, decision-making in breast reconstruction is as important as the surgical technique.¹⁴ Objective estimation of the contralateral breast volume and the 3D printed mold increase the surgeon's confidence in the reconstruction surgery.

A systematic review by Choppin et al⁹ assessed several methods to evaluate breast volume. MRI scanning consistently demonstrated the highest accuracy, with three studies reporting



Fig. 5 In a 52-year-old patient with right breast invasive ductal carcinoma, we performed nipple-sparing mastectomy and DIEP reconstruction using 3D surface scan and a printed mold: A, preoperative contour; B, 2 months after operation, breasts were symmetric. 3D, three-dimensional; DIEP, deep inferior epigastric perforator.

errors lower than 10%. The detail of anatomical boundaries, such as pectoralis major, mammary gland, subcutaneous tissue, and skin could be distinguished clearly in MRI. However, this examination was conducted with patients in a prone position, and it is not possible to inset the flap in the prone position during reconstruction surgery; thus, there is less value in creating the breast mold according to the MRI-scanned contour. MRI avoids the radiation exposure of CT scanning, but it is expensive and not routinely used in preoperative examination.

3D surface imaging is the latest and the most extensively studied technique of breast volumetric analysis. Galdino et al¹⁵ first used 3D surface scanners to quantify parameters such as volume

and shape to assess symmetry. There are various systems of 3D surface imaging. Among them, laser imaging, structured light, and stereophotogrammetry 3D scanning techniques are the most studied.¹⁶ In our study, the Artec Eva, which is a handheld 3D surface scanner, was used. It contains three cameras using the structured light method to conduct imaging with proven accuracy.¹⁷ Modabber et al reported a mean error of 0.23 ± 0.05 mm in the measurement of a scanned Lego brick attached to the forehead of a patient.¹⁸ In the current literature, it has been used in monitoring postoperative facial swelling after orthognathic surgery¹⁹ and in the assessment of volume and shape of lower extremity amputee stumps.²⁰ An advantage of the Artec Eva is



Fig. 6 This 32-year-old patient with left breast huge phyllodes tumor underwent mastectomy and DIEP reconstruction using 3D surface scan and a printed mold: A, preoperative breast contour; B, symmetric and nature contour upon 3 months follow-up. 3D, three-dimensional; DIEP, deep inferior epigastric perforator.

that it is a mobile scanner, giving the opportunity to obtain 3D images from any location. An additional advantage is that it is faster and less expensive than other imaging systems. It can also detect colors, allowing for the identification of anatomical landmarks. However, more experience and training are necessary to be able to correctly capture 3D images. Furthermore, manual data processing is required before the 3D image is adequate for analysis or surgical planning, which will take an experienced user a few minutes. Therefore, imaging with the Artec Eva is often performed by an experienced researcher. To the best of our knowledge, this is the first study combining Artec Eva scanning and postprocessing software to evaluate breast shape and volume. The accuracy, reproducibility, and reliability of 3D surface imaging obtained by the Artec Eva system were compatible with MRI in our study.

A systematic review of 3D surface imaging methods showed the high accuracy but larger uncertainty of 3D surface imaging when measuring absolute volumes.⁹ Inconsistency of breast landmarks,¹⁵ lengthy capture time,²¹ and definition of the non-visible chest wall interfere with accuracy. In our series, all breast landmarks were determined by the same surgeon (C.J. Feng) and a stable patient positioning was ensured during image capturing, which might help avoid artifacts and uncertainty. We compared the 3D surface scan of breast volume with water volume displacement of the mastectomy specimen, which revealed a strong correlation and validated our 3D scanning workflow; this result is consistent with the findings of Yip et al.²²

Tomita et al²³ described a similar method, which combined 3D surface scanning and a printed mold made of an acrylonitrile-butadiene-styrene copolymer (ABS). Both PLA and ABS are commonly used 3D printing materials, which share similar density, tensile strength, and cost. Due to its lower printing temperature, PLA, when properly cooled, is less likely to warp and can print sharper corners and features (printing details down to 0.8 mm) compared to ABS. PLA is ideal for 3D prints where aesthetics is important. While PLA is natively biocompatible, ABS is not as ideally suited for biomedical devices. Surface modification is needed to render ABS water impermeable, hydrophilic, and biocompatible.²⁴

Regarding the mold design, the holes we included make the flap visible during inset. Since it is possible to see the flap appearance through the holes during inset, signs of compromised blood flow can be detected immediately. Moreover, drilling holes randomly scatter over the mold. Using this method, we can ensure that the whole flap fits the mold and the neo-breast is mounded to the mirrored image of the contralateral breast. It takes 20 minutes to design the mold, 10 minutes for slicing, 15 to 20 hours for printing, and about 60 minutes to remove the support. Altogether, each mold costs 15 to 20 USD.

There are some limitations to our study. First, the sample size is relatively small. This also limits the variability of breast size and shape. Regarding the preoperative planning, breast borders are difficult to define in patients with high BMI; careful preoperative palpation is essential. Also, scanning large-breasted patients in the supine position might eliminate ptosis and increase accuracy.²¹ As for mastectomy specimen measurement, actual excised tissue might differ from the planned area. Lymph node resection should not be part of the mastectomy specimen, since excessive lymph node tissue interferes with the volumetric analysis. Additionally, oncologic safety and complications of nipple-sparing mastectomy and skin-sparing mastectomy have been proven to be not inferior to traditional mastectomy, nipple-sparing mastectomy, and skin-sparing mastectomy, thus becoming the choice of an increasing number of patients.^{25,26} Although the skin flap or nipple-areola complex volume is limited, it might interfere with the results of specimen measurement using water volume displacement. For the reasons given above,

we will perform a subgroup analysis of BMI, breast size, ptosis grade, and mastectomy methods to refine our results. According to the result of our study, estimation of breast volume by 3D surface image was comparable with MRI. However, the inability to detect chest wall contour by 3D scanning is a drawback; combining 3D surface scan and MRI might overcome this limitation. We hope to develop a novel modality combining 3D surface scan and MRI in the near future. We suggest to use 3D surface image for breast volume estimation in most situations. MRI should be taken into consideration when it comes to chest wall deformity. Further long-term follow-up, evaluation of aesthetic outcome, and the BREAST-Q questionnaire will be completed.

Using 3D surface imaging to evaluate breast shape and volume is a quick, effective, and convenient method. The accuracy, reproducibility, and reliability of 3D surface imaging were similar to those of MRI in our study. In addition, 3D-printed molds could achieve better symmetry and aesthetic outcomes in immediate autologous breast reconstruction.

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