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Systematic Review

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A systematic review of 3D printing in autologous breast reconstruction

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Abstract

Aim: The use of three-dimensionally printed (3DP), patient-specific models in autologous breast reconstruction is gaining popularity, namely for their benefits in surgical planning and ability to aid in aesthetic outcomes. Furthermore, 3DP patient-specific models serve as a safe alternative to intraoperative surgical training and act as a useful tool for visualizing the intramuscular course of deep inferior epigastric perforator vessels. Despite demonstrated usefulness in other surgical specialties and areas of plastic surgery, there remains a significant gap in the literature exploring specific perioperative, preoperative, and intraoperative uses as well as the educational advantages of 3DP in autologous breast reconstruction.

Methods: PubMed, MEDLINE, EMBASE, Scopus, and the Cochrane Central Register of Controlled Trials were searched for all English language articles using specific MeSH terms (3dp OR 3D-print* OR three dimension* print*) AND (breast reconstruction). Only studies discussing the use of 3DP for surgical planning or as an educational tool in autologous breast reconstruction were included. Studies using 3DP as interventions or implants were excluded.

Results: A total of 168 articles were identified, 13 of which were selected for inclusion. Risk of bias was low for 8 articles and moderate for 5 articles. Seven (53.8%) articles discussed 3DP usage in preoperative planning. Most papers (12, 92.3%) focused on 3DP models as guides for intraoperative identification of anatomical landmarks and 3DP molds as tools to achieve desired breast volume, shape, and projection. Only 4 (30.7%) articles discussed patient outcomes. Of the 4 (30.7%) articles that discussed education, only one of these properly assessed trainees and faculty using pre- and post-intervention surveys.

Conclusion: The majority of 3DP research as an intraoperative guide and educational tool is concentrated outside of autologous breast reconstruction. Studies that do discuss this have found significantly higher success rates in dissecting true DIEP flaps when 3DP vascular modeling is used and can result in improved confidence and competence in surgical training for microsurgical anastomosis. Although 3DP has been shown to aid microsurgeons in preoperative planning, most research concentrates on the aid of this novel technology in dynamic, intraoperative decision making. Existing research has identified five 3DP breast molds, but studies have yet to compare these molds in a controlled setting to assess for superiority in feasibility and outcomes. There is little investigation into the usefulness of 3DP as an educational tool, and more research should be conducted as this methodology expands to cover more forms of autologous breast reconstruction.

Keywords: 3D-printing, breast reconstruction, education, 3D model, 3D-printed model, flap model

INTRODUCTION

In recent decades, 3DP technology has revolutionized patient-specific care, surgical interventions, and medical education across numerous medical specialties[1]. Traditionally, surgeons have relied on two-dimensional imaging techniques such as computer tomography (CT) scans, magnetic resonance imaging (MRI), and X-rays to visualize anatomical structures, inevitably leading to challenges in accurately interpreting complex three-dimensional structures and planning for anatomic variation[2]. However, the advent of 3DP has bridged this gap by providing tangible, patient-specific anatomical models derived from medical imaging data[3]. These highly accurate 3DP models serve as invaluable tools for preoperative planning, allowing surgeons to explore and strategize interventions in a realistic, tactile manner.

Orthopedic surgery is described as one of the earliest medical specialties to adopt 3DP modeling and continues to implement this innovation through anatomic models[4], implants[5], and patient-specific instrumentation[6]. In the adjacent field of plastic surgery, 3DP modeling has transformed the landscape of subspecialties from craniofacial reconstruction to reconstruction of soft tissue defects[7]. In craniofacial surgery, creating precise 3DP models based on patient-specific CT scans enables surgeons to meticulously plan complex procedures involving skull defects, facial reconstructions, and cranial implants[8]. Furthermore, in reconstructive procedures following trauma or oncologic resections, the ability to create tailored 3DP models aids in devising optimal strategies for tissue reconstruction, ensuring improved functional and aesthetic outcomes[9]. While reconstructing soft tissue injuries, the use of 3DP technology has reshaped the surgical planning process[7]. Surgeons can visualize potential outcomes more realistically through 3DP models of patient anatomy[10] and determine viable autologous graft dimensions[10,11], facilitating informed decision making. Additionally, in procedures like autologous breast reconstruction, personalized 3DP models assist surgeons in determining optimal flap volume, shaping, and placement by serving as molds for shaping flaps, and intraoperative guides for vascular anatomy. 3DP molds can be modeled after pre-mastectomy breast or contralateral breast (in unilateral reconstruction), thereby enhancing surgical precision and patient satisfaction[12].

The usage of 3DP has been reported both as an intervention and in surgical planning in plastic surgery as a whole. However, there is little focus on the usefulness of these models in breast reconstruction, particularly in the realms of preoperative planning, intraoperative decision making, and as an educational tool for trainees. Furthermore, there exist gaps in tracking patient outcomes when 3DP models are used in autologous breast reconstruction. Our study aims to locate and characterize existing research and identify the milestones still to be reached in this area.

METHODS

Study selection

We conducted a systematic review of literature on 3DP in Breast Reconstruction with a focus on articles that mentioned 3DP educational value. A literature search was performed using PubMed, MEDLINE, EMBASE, Scopus, and the Cochrane Central Register of Controlled Trials with the MeSH terms: (3dp OR 3D-print* OR three dimension* print*) AND (breast reconstruction). We utilized the Covidence software (Melbourne, Australia) to maintain the study database. Study selection followed the Population, Intervention, Comparison, Outcome, Timing, and Setting (PICOTS) framework.

Inclusion criteria for articles were as follows: (1) patient population pursuing breast reconstruction surgery; (2) discussed 3DP used for surgical planning; (3) discussed 3DP used as an education tool; and (4) original scientific article. Exclusion criteria included: (1) studies discussing 3DP in non-plastic surgery; (2) non-breast reconstruction; (3) studies that used 3DP as an intervention; and (4) systematic reviews, literature reviews, and meta-analyses. There were no constraints on publishing year, as 3DP rendition from CT was invented in 2005[13].

Study workflow was managed using PRISMA guidelines[14] - two independent authors screened article full texts, titles, and abstracts that were identified using the aforementioned databases. Only articles whose primary objective was to describe the use of 3DP as an educational tool in Breast Reconstruction were selected. There were no discrepancies between reviewers. Risk bias for each study was assessed using the Risk of Bias in Non-Randomized Studies of Interventions (ROBINS-I) scale[15]. The authors extracted information on study objectives, design, interventions, results, and conclusions. The reference sections of articles that were selected for the final study cohort were also reviewed to identify any articles that may not have been found during the first round of article searches.

Data collection

The objective of this review was to assess the current collection of literature analyzing 3DP as an intraoperative guide and educational tool in breast reconstruction. This was done by characterizing intraoperative use and educational goals. Variables were collected in the “yes”/”no” format. The data dictionary, including variable names and guiding questions, is shown in Table 1.

RESULTS

Our review found that investigations into 3DP as an educational tool are widely lacking - of 136 articles identified with keywords, only 13 fit the criteria for discussing 3DP in this context. Figure 1 represents a flow diagram demonstrating the selection of the final articles chosen for review. Overall bias risk was low for 8 studies and moderate for 5 studies [Supplementary Figure 1].

All papers utilized similar methods for creating 3DP: patients first underwent a CT scan of the breast, and segmentation was performed. Subsequently, files were imported into processing programs and later printed as cured polymers. Polymer materials across studies included polyactic acid (PLA) filament[12,18,23,24,25,27], UV cured polymers[16,19], acrylonitrile-butadiene-styrene copolymer[17], and gray pro resin[21].

Table 1. This is a table caption. A summary description of this table should be written here

Section	Guiding Question	Totals	References
Preoperative Assistance	Was model used for preoperative planning?	7 (53.8%)	[16-22]
Intraoperative Assistance	Was model used for intraoperative guidance?	12 (92.3%)	[12,16-26]
Anatomical decisions	Was model used to guide the procedure via anatomical landmarks (e.g. perforator identification, dissection time)?	4 (30.7%)	[19-22]
Flap harvest	Were 3DP models assessed as an aid in flap harvest time?	1 (7.7%)	[16]
Flap shaping	Were 3DP molds used to guide flap shaping?	5 (38.5%)	[12,17,23,25,26]
Flap type changes	Were intraoperative changes to the *type of flap* discussed (e.g. MS-TRAM, full TRAM, DIEP)?	1 (7.7%)	[16]
3DP + other imaging	Was 3DP utilized with other novel imaging modalities?	1 (7.7%)	[24]
Patient Outcomes	Were patient outcomes reported?	4 (30.7%)	[16,17,22,25]
Education	Did paper mention 3DP use in education?	4 (30.7%)	[16,19,22,27]
Trainees	Were trainees included as subjects in education paper?	1 (7.7%)	[22]
Attendings/Faculty	Were attendings/faculty included as subjects?	1 (7.7%)	[22]
Pre/Post 3DP Use Assessments	Were pre-/post-intervention assessments implemented for users?	1 (7.7%)	[16]

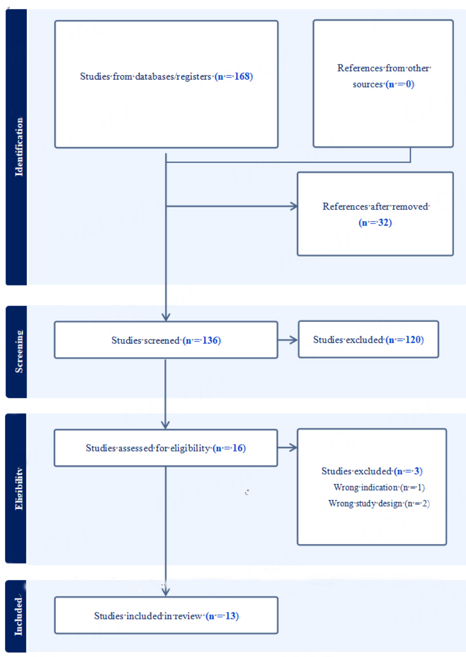


Figure 1. PRISMA study selection diagram.

Table 1 represents categorization of references, and summaries of relevance to category topic. A total of 7(53.8%) studies discussed using 3DP for preoperative planning. 12 (92.3%) articles discussed intraoperative guidance 3DP provided. Of these, 4 (30.7%) papers reported success using DIEP 3DP models for accurate intraoperative perforator identification. One (7.7%) reported 3DP impact on perforator identification time, and one (7.7%) paper focused on flap harvest time. One paper (7.7%) discussed changing the type of flap (e.g. msTRAM, full TRAM, and DIEP) intraoperatively. The majority of papers (5, 38.5%) discussed using 3DP molds to guide surgeons in shaping the flap to the desired breast shape and volume. Four (30.7%) articles discussed patient outcomes - 3 (75%) of those articles investigated 3DP feasibility and, therefore, did not compare 3DP usage with CT or other imaging modalities. Of 4 (30.7%) articles that mentioned 3DP use as an educational tool, only one (7.69%) article asked senior microsurgeons and trainees to evaluate 3DP for accuracy and usefulness using pre- and post-intervention surveys.

Categories of intraoperative 3DP models for breast reconstruction

Our review identified nine different types of 3DP models utilized for breast reconstruction covering three anatomical regions, shown in Table 2. Whole breast models were mainly utilized to match reconstructed breast volume with preoperative volume, and achieved this either with a full volume rendition of the breast (**2A**), or a full volume mold (**2B-F**). Abdominal wall models were created with the goal of perforator identification. Within this category, models were either renditions of portions involving surrounding abdominal volume(**2H**) or vasculature alone(**2I**). One paper created a model of thoracodorsal artery perforators(**2G**) to yield visualization of vasculature for a patient who had sustained extensive burn injuries[16].

Cost of production

Six papers in our review (46.2%) discussed the financial implications of 3D models. Hummelink *et al.* demonstrated that the total added cost for their mold was 20 euros, which they deemed negligible to total breast reconstruction costs[12]. Chae *et al.* cited their arterial mapping model costs between 3,000 and 6,000 AUD (Australian dollar)[22].

For domestic studies, four studies (30.8%) discussed the cost of models. The models utilized at Stanford University, featured in Ogunleye *et al.*, are not billed to the patient. The average cost of 3D printing models for unilateral breast reconstruction patients is $74.03 ± $29.07, and this cost is covered by the 3D printing laboratory[16]. Tomita *et al.* cited a cost of less than $5 per mold, but did not discuss which party was responsible for these costs[17].

Low cost-benefit ratio was reported as key for surgeons to adopt new technology in the postoperative interviews conducted by Nicklaus *et al.* after utilizing models printed via 3D photography[24]. Dr. Mayer presented an affordable alternative to obtaining 3D breast images and 3D printing models to assist in flap shaping. After obtaining 3D images of the breast with the 3D simulation technology Crisalix, the image is exported and then 3D printed. The reported cost of Crisalix was an annual subscription ranging from $1,761 to $6,082. The total cost of production of their model is $100 USD, and authors reported that these models reduce the need for surgical revisions of both reconstructed and contralateral breasts, translating to long-term cost effectiveness[25]. DeFazio *et al.*'s arterial guidance model had estimated costs of $829.72 per patient, an amount they deemed favorable compared to the $1,113 attributed to the average reduction in operative time[21].

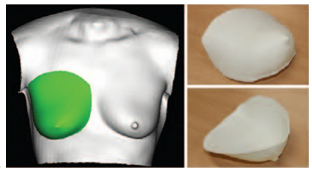
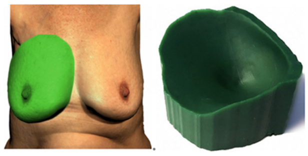
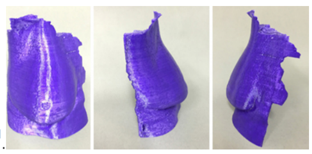
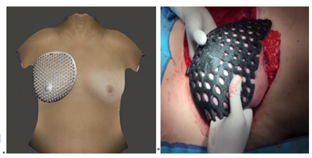
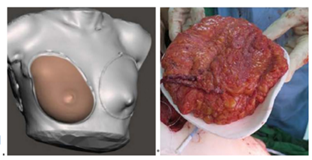
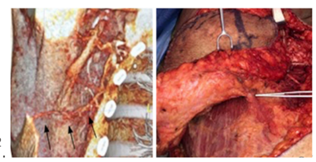
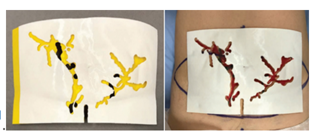
DISCUSSION

Selected literature involving 3D printing in autologous breast reconstruction mainly discussed preoperative planning, intraoperative usage, patient outcomes, and education.

Preoperative planning

Our group was interested in the extent to which the usage of 3DP was discussed in the context of preoperative planning. Only 6 papers discussed this, and their methods suggest a roadmap for the analysis of 3DP usage in future research. Ogunleye *et al.*, for example, captured the preoperative decisions on the type of flap for abdominal-based autologous breast reconstruction[16]. They also highlighted uses for 3DP in breast reconstruction related to burn injuries and breast cancer, emphasizing the benefit of using 3DP to visualize vascularity that would have otherwise proven difficult given the extent of the patient's burn injury[16].

Table 2. 3D Printed Models Used for Intraoperative Breast Reconstruction

Anatomical Region	Subtype		Totals	Ref.
Whole Breast	Whole Breast Full Volume Replica	2A[1]. 	1 (7.7%)	[24]
	Whole Breast Mold	2B[1]. 	6 (46.1%)	[17,26]
		2C[1]. 		[12]
		2D[1]. 		[23]
		2E[1]. 		[25]
		2F[1]. 		[18]
Chest Wall		2G[2]. 	1 (7.7%)	[16]
Abdominal Wall	Includes surrounding tissue	2H[3]. 	2 (15.4%)	[16,19]
	Vasculature only	2I[1]. 	3 (23.1%)	[20-22]

[1]Images adapted directly from referenced publications: 2A adapted from Nicklaus *et al*., 2021[24]; 2B adapted from Tomita *et al*., 2015[17]; 2C adapted from Hummelink *et al*., 2018[12]; 22D adapted from Chae *et al*., 2017[23]; 2E adapted from Mayer *et al*., 2020[25]; 2F adapted from Chen *et al*., 2019[28]; 2I adapted from Chae *et al*., 2018[20]; [2]Image 2G: Image of 3DP model not shown in the original paper. Image shown here is of 3D CTA reconstruction used to print the mold. Image adapted with permission; [3]Image 2H: Image adapted with permission.

Emphasis was placed on assessing usefulness via survey distribution. Survey results were stratified by flap-raising surgeon *vs.* second surgeon, and both groups found the model useful[22]. This group also emphasized marking the patient abdomen with 3DP outlines of vasculature[20,21].

Aside from predicting flap type and aiding trainees in visualization of vasculature, the main advantage of 3D-aided preoperative planning was the ability to utilize 3D reconstruction of CTA in predicting reconstructed breast volume. Taking 3D surface imaging of the bilateral breast region while the patient was in a sitting position allowed researchers to build models that would aid in achieving preoperative breast volume in reconstructed breasts[17].

Intraoperative usage

3DP models were utilized intraoperatively as two main modalities: as a reference tool to better visualize patient anatomy or used to mimic desired breast shape and guide shaping of flaps and fat grafting.

Anatomical guidance

Papers that discussed 3DP as an intraoperative anatomical reference tool discussed perforator identification, 3DP effects on perforator identification time, 3DP effects on flap harvest time, intraoperative changes to the flap type, and concurrent use with other novel imaging modalities to represent ideal breast shape. DIEP 3DP models were shown to aid surgeons in accurate intraoperative perforator identification, and this was achieved through various combinations of referencing the model throughout the operation and marking the patient abdomen preoperatively[19-22]. Chae *et al.* went so far as to suggest that marking the patient's abdomen using the 3DP model in order to inject contrast directly into perforators facilitates identifying perforator connection with subdermal plexus and flow pattern[20]. Defazio *et al*. also utilized 3DP to mark the patient abdomen and found that 90% of flaps harvested using DIEP 3DP models were successful compared with 58.6% using CT alone($P = 0.08$). This group emphasized that 3DP models aid in correctly identifying perforator number, source-vessel origin, and DEIA branching pattern, whereas CT interpretation alone yielded inaccurate depictions of branching pattern(28% of hemiabdomens) and perforator source-vessel origin(33% of hemiabdomens)[21]. Perforator identification was also discussed in the context of the time it took to accomplish this; one paper found that the use of 3DP model reduced intraoperative perforator identification by 7.29 minutes($P = 0.02$)[22].

Ogunleye *et al*. found that the usage of 3DP models as an anatomical guide resulted in a decrease in flap harvest time in bilateral autologous breast reconstruction ($P = 0.001$), and in cases where MS-TRAM was used ($P = 0.001$)[16].

One (7.7%) paper reported intraoperative decision changes to the flap type itself. Ogunleye *et al*. found no intraoperative decision changes for bilateral or unilateral DIEP or MS-TRAM cases compared with cases where CT alone was used to guide dissection[16].

One paper (7.7%) discussed applications of 3DP as an anatomical decision making tool with other modalities. Nicklaus *et al.* described the ability to collect 3D photographs and render 3D models intraoperatively during mastectomy procedures. Interviewed surgeons did not opt to replace 3D models with 3D photographs or augmented reality viewing, but rather preferred models in addition to 3D photographs[24].

Guiding flap shape

The usage of 3DP to aid in aesthetic and symmetric breast reconstruction involved adapting models to the whole breast. In patients undergoing post-mastectomy unilateral breast reconstruction, whole breast molds were utilized to mold flap tissue and/or tissue expanders to achieve contralateral breast symmetry. For patients who required bilateral breast reconstruction, molds were created using preoperative scans of natural breasts. This method was successful - minimal postoperative breast volume differences between natural and reconstructed breasts were measured, and in bilateral cases, there were small differences between preoperative and postoperative volume measurements. Tomita *et al.* reported using volumetric 3D reconstruction of patient whole breasts to aid flap shaping intraoperatively and found an excellent correlation ($r^2 = 0.99$) between estimated total flap volume and actual flap weight[17]. Their group was able to successfully apply this technique to patients with ptosis[26].

Another group introduced 3DP whole breast mold use concomitant with the St Andrew's coning technique, where circular rounds of suture are placed in the cutaneous layer of DIEP flaps to create the desired projection[23]. Mayer *et al.* introduced a porous mold that included the NAC for patients undergoing non-nipple-sparing mastectomy to better assist with flap shaping and achieving the desired projection[25]. Authors noted the importance of careful patient selection when using whole breast molds - patients should be satisfied with the natural breast on the unaffected side, and should have sufficient adipose tissue[12].

Patient outcomes

All papers that described 3DP model use intraoperatively reported standard patient outcomes including flap failure rate, takeback rates, and complications. Ogunleye *et al*. reported results of 116 patients, where 58 (50%) of patient procedures were performed with 3DP model and 58 (50%) patient procedures were performed with CT alone. There were no significant differences in flap takeback rates for unilateral or bilateral cases, and both groups had one incidence of hematoma[16]. Dr. Chae's paper in 2021 discussed a standard set of outcomes: reporting no immediate flap-related complication rates, a mean length of stay of 6.4 days, and no donor-site morbidity[22]. While Tomita *et al.* cited a 75% cosmetic satisfaction rate for breast reconstruction following the intraoperative use of 3DP model to aid surgeons in restoring pre-mastectomy volume, they did not compare this rate to a group where the volume was not used[17]. Patient outcomes were not linked to the presence or absence of 3DP model when the model was not used to shape the flap intraoperatively. Patient outcomes reported when 3DP mold *was* used intraoperatively to shape the flap were positive. Patients rated the 3DP image acquisition process as simple, and were satisfied with the results of their procedure[25].

Education

Only one paper used 3DP models *exclusively* in an educational setting. Papavasiliou's group developed a 3DP chest wall to augment the standardly utilized chicken thigh model for teaching of end-to-end anastomosis during DIEP breast reconstruction. Researchers 3D-printed a chest wall that is to be added to the chicken thigh model in order to increase depth perception and more closely mimic the complexity of anastomosis during DIEP procedures. Briefly, the anterior chest wall model is placed perpendicular to target vessels and parallel to the sternum, and blocks are added between ribs to reduce vessel exposure and mimic intercostal muscles[27].

Mehta *et al.* mentioned that trainees successfully used 3DP models preoperatively and intraoperatively to identify the intramuscular course of DIEP perforators[19].

Chae *et al.* conducted the only survey in this literature search that compared various roles surgeons take during an autologous breast reconstruction case or subsequent management. This held true when comparing faculty to trainees save for the usefulness of the device in intramuscular dissection - there was a trend demonstrating that trainees found the device more useful for intramuscular dissection ($P = 0.07$)[22].

Future directions

Intraoperative use of 3DP, described here in two main modalities, offers many possibilities for future clinical use. Only one paper described 3DP as an anatomical guide in breast reconstruction procedures that did not involve abdominal-based flaps—the opportunity to apply 3DP models to other forms of autologous breast reconstruction remains. While five different whole breast molds were used intraoperatively, a comparison of these molds in a controlled setting has not yet existed to assess for superiority in feasibility and outcomes.

Educational assessments into 3DP both as an intraoperative mold, intraoperative guide, and training tool are severely lacking in the literature. Groups that developed intraoperative techniques augmented by 3DP should consider assessing whether these are useful in the teaching environment. For example, while one group provided the first use of 3DP modeling to specifically augment the educational experience, they did not evaluate this model by assessing its usefulness to trainees.

There remains a general gap in the literature investigating the usefulness of 3DP in breast reconstruction. In fact, only three more articles discussing breast reconstruction appeared in our search versus the search by Bauermeister in 2016[29]. Furthermore, Dr. Michael P. Chae's work constituted 3 (23.07%) of all identified relevant articles for this review, and these articles did not duplicate data[20,22,23].

Study limitations

This study was not without limitations. While we utilized multiple databases, it is possible that the search strategy did not capture all relevant articles. There is also the risk of bias reporting that is inherent to all studies with the systematic review design. Using two independent reviewers for information extraction helped minimize bias risk. Finally, the heterogeneity of data does not allow for pooled analyses.

Conclusions

Preoperative and intraoperative use of 3DP as an anatomical guide was shown to reduce the time it took to identify perforators and harvest the flap, and was useful in visualizing anatomy in complex burn reconstruction. The varied intraoperative use of 3DP whole breast models described here represents a new frontier for achieving symmetry and favorable aesthetic outcomes in breast reconstruction. Researchers showed that five different models can be used to shape abdominal flaps to achieve the desired shape and projection, and that these can be integrated with various forms of flap arrangement. Investigations into the usage of 3DP as an educational tool are few, and those with this focus show mixed results when comparing the sentiments of trainees and senior microsurgeons toward its use. This review demonstrates the necessity for more research into 3DP use in autologous breast reconstruction.

DECLARATIONS

Authors' contributions

Study conceptualization, statistical analysis/interpretation, manuscript drafting, revision, and submission: Carrion K, Bernal C

Critical points of data analysis, manuscript revision: Akhter MF

Provided administrative, technical, and material support: Cox E, Krakauer K
Study conceptualization, manuscript revision, and submission: Mohan AT, Nazerali RS, Lee GK, Nguyen D

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Conflicts of interest
All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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