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Review Article

The Present and Future of Robotic Surgery in Breast Cancer and Breast Reconstruction

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Abstract

Background: Breast cancer is the second most common cancer in women with an improving mortality rate and growing need for reconstruction following oncologic resection. Advancements in robotic surgery and minimally invasive techniques have offered refinement to traditional open techniques of flap harvest for reconstruction, particularly regarding improved donor site morbidity.

Methods: The literature review was based on a pub-med database search using the keywords "Robotic breast reconstruction" in conjunction with the Boolean operators "Flap," "Latissimus," and "DIEP" to specify the search. 106 Results were generated, which were then manually reviewed and condensed for a comprehensive stance on the current status, technique, variations, and outcomes for robotic breast reconstruction.

Results: Robotic technique has been described for the latissimus dorsi (LD) and deep inferior epigastric perfo-rator (DIEP) flaps for breast reconstruction. For LD, robotic flap harvest reduces donor site morbidity, incisional length, hospital length of stay, with similar complication rates for seroma/hematoma/infection, and longer op-erative times. Robotic LD procedures have been described in conjunction with single site nipple-sparing mas-tectomy and flap elevation leading to a full minimally invasive resection and reconstruction from one lateral incision. Robotic DIEP harvest offers a considerably smaller fascial incision/rectus muscle dissection and has a comparable complication rate to traditional technique with shorter hospital length of stay, and improved pain, at the expense of longer operating times. Data on hernia/bulge reduction from robotic technique is limited and not yet available.

Conclusion: Robotic breast reconstruction offers great potential for improving breast reconstruction in terms of donor site morbidity, length of incision, hospital length of stay at the cost of longer operating times, and in-creased technical skill/ specialization, but it has yet to be proven on a large scale with long-term outcome data. Multicenter, prospective clinical data and trials are needed to help elucidate the potential for equivalence and superiority of the minimally invasive approach compared to standard open techniques, but the future is prom-ising for robotic surgery in breast cancer and breast reconstruction.

Keywords: DIEP; Da Vinci; Latissimus dorsi; Plastic surgery; Robotic breast reconstruction; Robotic surgery

Abbreviations

The following abbreviations are used in this manuscript:

MDPI:	Multidisciplinary Digital Publishing Institute
DOAJ:	Directory of open access journals
LD:	Latissimus Dorsi
DIEP:	Deep inferior epigastric perforator
TAP/TAPP:	Transabdominal pre-peritoneal
TEP:	Total extra-peritoneal
TRAM:	Transverse rectus abdominal muscle
UNLV:	University of Nevada Las Vegas
CT:	Computed Tomography
SP:	Single port

Introduction

One of the most common reconstructive challenges faced in the modern age is that of breast reconstruction. While the lifetime risk of developing breast cancer is about 1 in 8 for women in the US, the mortality rate has reduced by 58% through improved screening and treatment advancements over the last half century [1]. With the rising frequency of breast cancer operations/ oncologic resections, the need for restorative surgeries is growing as well. In the US, the long term trend of breast cancer has decreased mortality and decreased severity at presentation largely attributable to improved screening, treatment algorithms, and detection [1,2]. Oncologic breast surgery has evolved from the early days of radical mastectomy to modified radical mastectomy to skin-sparing mastectomy, to nipple-sparing mastectomy [3]. Focus on preserving appearance and contour has been paramount in the evolving trends of breast surgery. In the US, access to breast reconstruction is assured by the Women's Health and Cancer Rights Act (WHCRA) of 1998 [4]. Breast reconstruction techniques have evolved with two main categories arising; Implant based

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reconstruction and autologous flap-based reconstruction. Implant based reconstruction is the more traditional of the two with many similar concepts from cosmetic breast augmentation. A major pitfall with implant based reconstruction is the drawbacks associated with a radiated field. There is a higher rate of scar tissue formation, capsular contracture, and long-term deformity and the optimal reconstructive strategy is delayed autologous reconstruction [5]. Autologous flap based reconstruction overcomes many of these flaws by bringing the patient's vascularized non-radiated tissue/skin into the operative/radiated field. Autologous reconstruction decreases the risk of capsule formation/contracture, implant rupture/replacement, can provide additional skin, and can be neurotizednecrotized to restore a degree of sensation. Drawbacks to autologous reconstruction include selective patient candidacy based on habitus, donor site anatomy, morbidity/ complications, longer operative times, and complications associated with pedicle dissection and microsurgery [6]. Autologous reconstruction is favored in breast cancer patients having undergone radiation but is selective and contingent on the individual characteristics of each patient.

There are two classes of flap-based reconstruction- free flaps and pedicled flaps. Pedicled flaps are vascularized tissue elevated from a nearby body part and inset to the desired site with their original blood supply intact. Free flaps are tissue from another body part with the blood vessels being transected and re-anastomosed in a new connection [7]. Latissimus Dorsi (LD) and Deep Inferior Epigastric Perforator (DIEP) flaps have risen as the most common flaps for breast reconstruction. The LD flap is typically harvested as a pedicled flap in conjunction with an implant but can also be used by itself for small volume breast defects in the case of partial mastectomy/quadrantectomy or in the case of Poland syndrome which includes agenesis of the pectoralis muscle and chest wall deformity [8,9]. The DIEP is a myocutaneous flap first described in the early 1990s and popularized by Blondeel that ultimately replaced the pedicled and free transverse rectus abdominis muscle flap (TRAM) [10-12]. The DIEP gained dominance for abdominal based reconstruction due to a lower donor site morbidity, reduced risk of hernia/ bulge, bilateral capability, and cosmesis with the appearance of abdominoplasty. The DIEP is the gold standard today for fully autologous breast reconstruction, particularly useful in the setting of radiated fields. Additional more exotic options have arisen including the superior gluteal artery perforator (SGAP) flap, profunda artery perforator flap (PAP), superficial inferior epigastric perforator (SIEP), transverse upper gracilis (TUG) flap, and the lumbar artery perforator (LAP) flap although the DIEP is the most prolific option for total autologous reconstruction [13].

Endoscopic flap harvest techniques have been developed to reduce morbidity and incisional length but are considered very technically difficult with limitations in instrument mobility, 2 dimensional visualization, and have not gained much popularity as a result of technical challenges [14-16]. The robotic approach allows for a similar minimally invasive approach with greater dexterity and potential to overcome the laparoscopic technical limitations [17].

The National Aeronautics and Space Administration (NASA) and the United States military initially invested in robotic assisted techniques in hopes of creating a "telepresence" surgery where the surgeon could be in a different place from the patient. However, due to technological and practical constraints, this effort was transferred to Intuitive Surgical for their da Vinci platform. Robotic assisted surgery was first approved by the FDA in 2000 for the da Vinci Surgical System and has since revolutionized modern surgery [18]. General advantages of robotic surgery include tremor elimination, enhanced precision, improved ergonomic positioning, and 3D magnification. Robotic surgery has been found to reduce morbidity for patients with decreased intraoperative blood loss, shorter hospital stays, reduced pain, and faster recovery [19-21]. The da Vinci robotic platform's use has expanded from laparoscopic abdominal/ pelvic based surgeries to the chest, head/neck, and soft tissues [22]. Robotics in plastic/reconstructive surgery is a relatively new concept with a slower embrace due to large spacial tissue defects and the vast majority of open and non-cavitary procedures. The initial utilization of robotic assistance in breast reconstruction was for the dissection of the internal mammary vessels followed by the traditional free flap approach in 2006 [23]. This particular technique offered increased length for the anastomosis but did have a high hematoma complication risk.

The robot was introduced to breast reconstruction in 2012 through a novel study that demonstrated improved outcomes, paving the way for further expansion of robotic techniques in the field [17]. A review of most contemporary literature reveals two promising techniques for robotic assisted breast reconstruction: the latissimus dorsi (LD) flap and the deep inferior epigastric perforator (DIEP) flap [24,25]. Furthermore, mastectomy techniques have also been developed using the robot platform to perform minimally invasive quadrantectomy, partial mastectomy and nipple sparing mastectomy [26]. Advances in the Da Vinci Sp (Single Port) robotic platform that have allowed for advances culminating in true single incision mastectomy and LD reconstruction [27]. Overall, minimally invasive techniques are appealing for lower donor site morbidity, lower hospital length of stay, and improved cosmesis at the expense of operative time, and surgeon learning curve.

Materials and Methods

Literature review was conducted using a PubMed database search with the MESH terms "Robotic breast reconstruction" combined with the Boolean operators AND "Flap" AND "Latissimus", OR "DIEP" to refine the search. The search was limited to studies published in English and published before November 2024. A total of 106 results were generated, which were then manually reviewed. Duplicates and non-contributory articles were removed with a remaining 73 articles. These were further manually reviewed for a total of 26 articles reporting operative data and summarized to provide a comprehensive overview of the current status, techniques, variations, and outcomes of robotic breast reconstruction. Cadaveric studies were excluded. Of the studies fulfilling the inclusion criteria, there were case series, case reports, and retrospective case control/ cohort reviews. Internal review regarding ethics of the study was not necessary as all information was gathered from previously published and publicly available sources (Figure 1).

Results

Robotic-Assisted latissimus dorsi (LD) flap breast reconstruction

The LD pedicled flap is a well-established option for breast reconstruction, particularly for patients not eligible for an abdominal based autologous reconstruction [28]. LD flaps are often selected for patients with smaller body habitus and have an intact thoracodorsal blood supply, which may be injured during the index oncologic operation particularly if there was an axillary lymph node dissection [29].

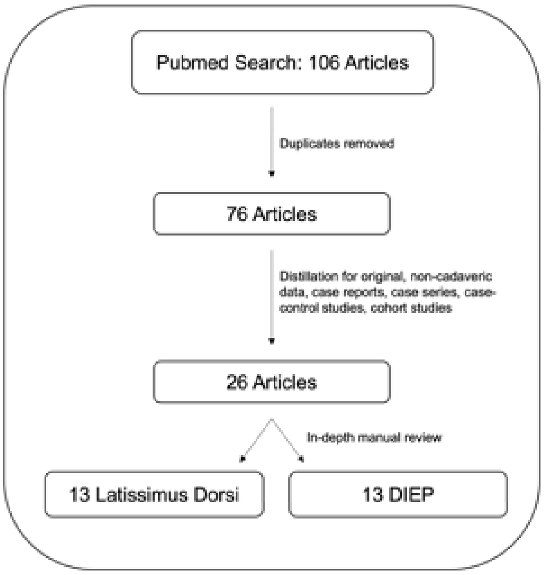

Figure: 1 PubMed database search with the MESH terms "Robotic breast reconstruction" combined with the Boolean operators AND "Flap" AND "Latissimus", OR "DIEP" to refine the search, followed by application of inclusion criteria and manual review.

Traditionally, the open LD flap requires a long incision, 15-45 cm in length, where the LD is carefully dissected, paying special attention to the pedicle thoracodorsal artery and vein. Alternative endoscopic harvest techniques have been described with similar complication rates, improved incisional length, and post-operative pain, but they also face technical challenges with limited mobility and difficult dissection [14,15]. The pedicled latissimus flap is elevated and tunneled under the skin to the mastectomy site to provide implant coverage and inframammary fold support. Multiple variations of the robotic LD flap harvest exist with variations in port placement, insufflation, and combination with robotic nipple sparing mastectomy. The major advantages of robotic LD harvest are that it allows for a smaller incision, improved cosmesis, and decreased hospital length of stay.

The first robotic-assisted LD flaps were completed by Selber et al. in 2012 in a case series (n=8) with promising results. The robotic harvest technique employed a short axillary incision for pedicle dissection and two to three additional ports with 10 mmHg insufflation for robotic instrumentation as opposed to a 15-45 cm incision in the traditional open technique. The robot was used to elevate the LD from the proximal port sites and release it from its distal origin and insertion sites with drain placement at the port sites. In the case series, robotic time decreased from 2 hours 35 minutes to 1 hour 5 minutes from the first to the last patient (Average 1 hour 51 minutes). One reported complication of contralateral transient radial nerve palsy related to positioning. No donor site hematoma/seroma or skin complications [30].

Clemens et al. published the next major robotic LD study in a 2014 retrospective cohort study based on Selber's technique which evaluated 12 robotic LD flaps compared to 76 total open technique (TOT) flap harvest in patients undergoing treatment with immediate tissue expansion, similar levels of radiation, and timing for delayed reconstruction. Robotic flap harvest had a decreased complication rate, 16.7% robotic vs. 37.5% TOT (p=0.31), including decreased seroma (10.9% versus 8.3%), infection (14.1 versus 8.3%), delayed wound healing (7.8% versus 0), and capsular contracture (4.7% vs. 0), although not statistically significant likely due to small sample size. Robotic LD had a longer operative time on average 1 hour 32 minutes compared to 58 minutes open. Decreased average hospital length of stay 2.7 (2-3) in the robotic LD group vs. 3.4 (3-6) in the open. At one year follow up, the robotic cohort had similar surgical complication rates, including seroma, capsular contracture, and wound healing [31].

A trans-axillary gasless robotic LD harvest was described by Chung et al. in 2015. A long retractor and 2 additional port sites were used in 12 patients who underwent robotic LD flap reconstruction, 3 delayed breast reconstructions, 4 immediate reconstructions with nipple sparing mastectomy, and 5 patients undergoing chest wall reconstruction for Poland Syndrome. The average robotic time was 85.8 minutes, the average operative time was 400.4 minutes, average docking time and robotic time decreased throughout the case series. This study also reported survey based patient satisfaction scores averaging 9.2/10 for breast symmetry, 9.9/10 for scar appearance, and 9.6/10 for general esthetic over a 15.7 month follow-up period [28].

The first case report for immediate robotic LD harvest following robotic quadrantectomy was performed in 2018 by Lai et al. for a patient with T3N1M0 breast cancer who underwent neoadjuvant chemotherapy followed by robotic left upper lateral quadrantectomy and robotic latissimus flap harvest through an axillary incision and two port incisions. The robotic time was 267 minutes but had decreased to 97 and 90 minutes during subsequent author operations. This case was complicated by donor site seroma that resolved with serial aspiration outpatient [32].

A series of 23 robotic nipple sparing mastectomy with robotic LD harvest was performed by Houvenaeghel et al in 2019. 17 With LD flap alone, 6 with LD flap and implant. While this study focused primarily on robotic nipple sparing mastectomy and difference in robotic mastectomy dissection technique, it did highlight a learning curve of 10-11 operations to establish a consistent learning curve for robotic nipple sparing mastectomy and LD reconstruction. This was followed by a separate analysis of 80 robotic LD flaps with 71 immediate robotic LD flap reconstructions and 8 delayed reconstructions. This series was performed with a 4-7 cm axillary incision varying on habitus, gel port, and two separate robotic trocars at 7 mmHg insufflation. Median surgery time was 301 minutes. Complication rate of 41% with 29 patients developing donor site seroma and 1 patient who developed a donor site hematoma requiring reoperation. Average hospital stay of 4 days [33-36].

Houvenaeghel et al. published another study comparing open LD harvest and robotic LD harvest in skin-sparing mastectomy with immediate reconstruction. 46 robot 16 with implant, 59 open 7 with implant). The open LD group had a higher rate of neoadjuvant chemotherapy 50.8% vs. 19.6% p=0.001, previous radiation 66.1% vs 30.5% p<0.0001. Higher rate of sentinel node biopsy in the robotic group 53.5% vs. 22% open p=0.016. Median anesthesia/ surgical time was higher for robotic group 356.9/290.5 minutes compared to 327.5/259.7 minutes open. Breast implants with LD were associated with longer operative times and slightly longer hospital stay. Similar complication rate but there was a difference in severity of complications upon univariate analysis with higher severity in the robotic cohort requiring reoperation (2 vs. 1 open) [37].

Moon et al. published a 2020 case series of 21 robotic LD flaps performed for Poland syndrome. This was the first case series dedicated to Poland syndrome reconstruction. 5-6 cm axillary incision with 3 robotic ports and an axillary retractor. Lateral decubitus positioning. Average hospital length of stay 7 days. Low complication rate of 19% with 4x seromas and 1 axillary wound complication. 15 patients required re-operation 7x breast augmentations, 8x lipofilling procedures, 4 contralateral breast surgeries [38].

Wincour et al. published a 2020 retrospective cohort study in which 52 LD flaps were evaluated. 25 Robotic, 27 Open. Longer operative times were observed with robotic technique averaging 388 (245-519) vs. 311 (171-488) open. Similar complication rates were reported although there was a notably higher rate of seroma 19% vs. 0% open. Shorter hospital length of stay in the robotic group with average of 2 vs 3 days. The authors also found a lower but not statistically significant opioid use in the robotic group [39].

Joo et al published a 2021 case report using single incision robotic NSM and Robotic LD using the Da Vinci SP system. 4.5 cm axillary incision through which both procedures were performed. Comparable time to other robotic LD flaps was observed and without additional ports. 100 minutes console time, 15 minute docking time, no complications, and above average breast -Q patient satisfaction score 67 vs. 55/100 author average [27].

Cheon et al. published a 2022 retrospective case series from S. Korea overview of 10 years of robotic LD flap harvest and evolution from DaVinci Si 2012-2014 to Xi 2014-2018 to SP 2018-2021. Technique had changed drastically from the Si and Xi multiport platforms to single port system with retractor and 3 additional port placements to single port with insufflation. Si 1 infection (7.7%), 5 seroma (38.5%), 2 Donor site morbidity (15.4%), 8 wound problems (61.5%) Xi 2 infections (11.1%,) 6 seroma (33.3%), 1 flap loss (5.6%), 4 donor site morbidities (22.2%), 10 wound related problems (55.6%), Sp 1 hematoma (10%), 2 seroma (20%), 2 donor site morbidities, (20%), 2 wound related problems (20%). No significant difference in complication rate between groups although it is notable that the SP group had a lower wound complication rate and seroma rate. Study applied aesthetic scores from pre and postoperative photographs from 4 plastic surgeons with no significant difference between the groups [40].

Hwang et al. published a 2022 case series of 3 patients with Poland syndrome who underwent chest wall reconstruction with Da Vinci SP system. 2 males, 1 female that had an implant and contralateral robotic augmentation as well. No reported complications, 5 cm axillary incision. Greatly reduced robotic docking time 8.67 minutes (4-14) compared to previously reported averaging 23-55 minutes [41].

Eo et al. published a 2024 Korean single-institution first of its kind study comparing robotic, endoscopic and open LD reconstruction following partial mastectomy. 17 Endoscopic LD, 20 robotic, 20 open cases were performed. Robotic technique used an axillary incision and single inferior port using the Da Vinci Si system. There was a significantly longer average operative time for robotic (394.4) compared to endoscopic (316.6) and open (279.8). Significantly higher robotic time than endoscopic operative time (robot 75.7+-30.7, Endoscopic 34.5 +-12.9 $p<0.001$). No significant difference in opioid use among techniques. No significant difference in hospital length of stay. No significant difference in complication rates. There was a significant difference in patient satisfaction using patient survey modified BREAST-Q scores, with higher rates of patient satisfaction for robotic/endoscopic LD compared to open for posterior scar and overall, but no difference between robotic and endoscopic techniques [16].

Robotic-Assisted Deep Inferior Epigastric Perforator (DIEP) Flap Breast Reconstruction

DIEP flap breast reconstruction has emerged as the gold standard for autologous flap based reconstruction. The DIEP flap is based on perforating vessels from the deep inferior epigastric artery which provides blood supply extending from the external iliac artery/vein to the abdominal wall musculature, subcutaneous adipose, and skin. The DIEP is anastomosed to the internal mammary artery/vein in the chest or to the thoracodorsal vessels laterally to achieve breast reconstruction. Robotic assistance has been applied in dissecting the recipients internal mammary vessels as well as the establishment of the robotic DIEP harvest in dissecting the vascular pedicle [23]. One of the major shortcomings in traditional DIEP harvest is abdominal rectus muscle and anterior fascia damage to isolate the vascular pedicle leading to increased rates of hernia and abdominal bulging despite fastidious primary closure. Rates of hernia/abdominal bulge have been reported to be between 0.18% and 1.26% with associations with prior abdominal surgery, pregnancy history, smoking and age [42]. The robotic DIEP harvest sets out to improve this complication rate. Two methods of minimally invasive DIEP harvest have been described; a trans-abdominal preperitoneal (TAP) approach by Gundlapalli (2018) and Selber (2020) and the total extraperitoneal (TEP) approach first described laparoscopically by Hivelin (2018). The difference being for the TAP approach, the peritoneal cavity is entered and the vessels are dissected with a peritoneal flap and the TEP approach uses insufflation between the peritoneum and abdominal wall to isolate and transect the vessels without entering the peritoneal cavity.

The first robotic DIEP harvest was described by Gundlapalli et al. in a 2018 case report. A Robotic DIEP flap performed in a patient with previous neoadjuvant chemotherapy, modified radical right mastectomy, and adjuvant radiation. Left hemiabdomen DIEP flap was elevated with 1.5 cm fascial incision and 10 cm pedicle length with 20 minute robotic docking time and 40 minutes of console time. The authors claim 40 minutes is comparable with open pedicle dissection. Pedicle was dissected using a TAP technique with robotic running suture closure of the peritoneum. Four robotic ports were placed on the contralateral anterior axillary line. No immediate complication occurred immediately at either the flap or donor site or at 9 month follow up. Cost analysis was $16300 patient charge for robotic procedure and $14800 for typical open procedure [24].

Selber published a technique article outlining trans-abdominal pre-peritoneal DIEP harvest (TAP). The described technique uses three ports on the contralateral side identical to robotic rectus muscle flap port placement and a reported 1.5-3.0 cm fascial incision and 10-15 cm of pedicle length. Large emphasis was placed on pre-operative planning with CTA and favorable perforator anatomy with short intramuscular course and 1-2 closely grouped perforators. Authors reported a subjective decrease in pain and hospital stay [43].

Choi et al. Described the first extraperitoneal (TEP) DIEP harvest in 2021 utilizing the Da Vinci SP system and placing the single robot port through the neo-umbilicus. This method conserves the posterior rectus sheath and does not enter the peritoneal cavity reducing the risks associated with abdominal surgery (Bowel injury, adhesions, etc.) 17 of 21 DIEP patients were performed with this method from 9/2019-8/2020 with inclusion criteria being an intramuscular vascular segment <5 cm. The described technique involved 1.5 cm incision on the ipsilateral linea semilunaris for blunt finger dissection in the extraperitoneal space followed by 2 cmx2 cm cross incision at the new umbilicus for the robot port. Muscular pedicle dissection is performed open, followed by robotic dissection to the origin at the external iliac. Average robotic time 65+-33 mins. Average surgery time 487+-93 mins. Metrics on complication rate, hospital length of stay, comparison to open technique, or follow up were not published [44].

Kurlander et al. (including Selber) published a retrospective study analyzing preoperative CT angiogram for Robotic DIEP eligibility from 2017-2021. CT angiograms were reviewed for 49 patients (98 hemiabdomens). Inadequate or no perforators were identified on CTA in 18% of hemiabdomens. Mean predicted robotic and open DIEP fascial incisions were 3.1 cm and 12.2 cm, respectively, giving robotic approach fascial incision benefit of 9.1 cm ($P < 0.001$). The predicted robotic incision avoided crossing the arcuate line in 71% of hemiabdomens. Thirteen patients (28%) underwent robotic DIEP harvest. Actual robotic fascial incision length averaged 3.5 cm, which was not significantly different from the mean predicted fascial incision length ($P = 0.374$). Robotic DIEP flaps had fewer perforators (1.8 versus 2.6, $P = 0.058$). 27% of patients analyzed underwent robotic DIEP and the authors proposed more patients were eligible for the procedure than those receiving. A large emphasis was also placed on having an anterior fascial incision above the arcuate line to minimize the risk of hernia with an intact posterior rectus sheath [45].

Piper et al. published 2021 four patient case series from UCSF for TAP robotic DIEPs. Notably the included patients also underwent another robotic intra-abdominal procedure at the same time as bilateral DIEP harvest and breast reconstruction minimizing a need for a second operation. The first patient also underwent gastric resection for benign mass. Pedicle dissection time was 38 minutes, Hospital stay was 10 days. The second patient was BRCA2 positive and underwent prophylactic oophorectomy during the same operation. DIEP pedicle dissection time was 42 minutes, she was discharged on hospital day 2. 3rd patient was BRCA2 positive and underwent robotic hysterectomy and bilateral salpingo-oophorectomy. Pedicle dissection time was 52 minutes and hospital stay was 2 days. 4th patient BRCA2 positive and underwent concurrent hysterectomy and bilateral salpingo-oophorectomy. Pedicle dissection time was 48 minutes and she was discharged after 2 days of hospitalization. Notably, this was the first time a bilateral DIEP flap harvest was performed with another intra-abdominal procedure [46].

Shakir et al. performed a 2021 retrospective cohort analysis of endoscopic DIEP compared to laparoscopic TEP and Robotic TAP. 94 Patients underwent endoscopic DIEP harvest, 38 underwent TEP LAP harvest, and 3 patients underwent robotic bilateral reconstruction. All 3 robotic patients underwent synchronous additional intra-abdominal procedures at the time of operation; 2x abdominal hysterectomy and bilateral salpingo-oophorectomy and 1 partial gastrectomy. Average operative times varied from 249 minutes for a unilateral endoscopic DIEP, 535 minutes for bilateral endoscopic harvest, 335 minutes for unilateral TEP laparoscopic harvest, 453 for bilateral TEP laparoscopic harvest, and 535 for bilateral TAP robotic harvest. 5/142 Endoscopic and 2/67 TEP Lap patients had perforator injuries during dissection 0/3 in robotic cohort. Endoscopic cohort had 1x arterial thrombus, 3x venous congestion and TEP laparoscopic cohort had 1x venous congestion. No robotic complications reported. Cost analysis was performed with additional increase of approximately ~$234 per case of disposable cost endoscopically, ~$495 for TEP laparoscopic harvest, and ~$1487 for TAP robotic harvest. The average length of stay significantly differed, as subjects in the TAP robotic cohort remained in the hospital for an average of 4.7 days versus 2.8 and 2.5 days in the endoscopic and TEP laparoscopic cohorts. This increased length of stay in the robotic cohort is skewed by additional procedures performed for robotic cohort patients. Overall the authors prefer laparoscopic TEP technique and the study has confounding variables as the all patients in the robotic DIEP cohort also underwent concurrent intra-abdominal procedures [47].

Wittessaele et al. published a 2021 case series of 10 TAP robotic DIEP flaps. All flaps were unilateral with ipsilateral docking of the robot and 3 ports. Average docking time was 27.5 minutes (16-40), average fascial incision was 3 cm, average console time was 86 minutes (52-162), surgery duration was 479 (409-552). Patients were followed up at 2 and 6 weeks. No intra-abdominal complication or flap loss. 1x Hematoma occurred at the recipient site requiring evacuation. Authors are supportive of robotic surgery, had no prior robotic experience and are confident that with additional practice, operative time will be comparable to open with considerably smaller fascial defect [48].

Lee et al. published a 2022 retrospective cohort study comparing 186 open unilateral DEIP flaps to 21 unilateral TEP single port robotic flaps. Technique was similar to previously described with single robotic port at the neo-umbilicus. There was found to be a longer operative time in the robotic cohort (509+-71 vs. 438 +-83) but significantly decreased length of stay (7.92+-1.2 vs. 8.77 +-1.74), improved pain scores, less narcotic use and significantly higher scores for post-operative psychosocial well-being ($p=0.007$), physical well-being of the chest ($p=0.028$), and physical well-being of the abdomen ($p=0.02$). Complications were reported 5.3% (1) Flap loss, 5.3% (1) Fat necrosis in the robotic cohort and 2.2% Flap loss (4), 1.1% (2) fat necrosis, 1.1% (2) Seroma, 6.5% (12) donor site wound problem in the open cohort [49,50].

Jung et al. published a 2022 case report of a patient that underwent robotic nipple sparing mastectomy with immediate single port TEP robotic DIEP. No complications, 7 day hospital stay and 7 month follow up. This was the first report of a fully robotic resection and immediate DIEP reconstruction using the Da Vinic SP system [50].

Bishop et al. published a 2022, 21 patient case series on multiport TAP robotic DIEP reconstruction. 10% of patients had a prior intra-abdominal surgery. Average fascial incision was 3.6 +-1.6 with an average pedicle length of 13.3 +-1, console time of 45+-9 minutes, total surgery duration of 425+-70 unilateral, 511+-67 bilateral. Average hospital stay was 3.8 days +-0.9. Average follow up of 5 months, 31.3%(5) Surgical site occurrence, 1x wound healing complication, no flap loss or hernia/ bulging. Post-operative pain analysis was performed in which 5 patients had bilateral flaps, one harvested robotically and the other open and were blinded to which side was harvested robotically. 4/5 patients reported less pain on the robotic side with bilateral TAP blocks. Analysis of CTA positive predictability of fascial incision was 86% accurate within 2 cm/75% standard difference of predicted fascial incision from CT scan, validating CTA as a reliable pre-operative planning modality for robotic DIEP candidacy [51].

Tsai et al. Published a 2023 retrospective cohort study comparing 13 (11 unilateral 2 bilateral) robotic DIEP flaps to 86 (62 unilateral, 24 bilateral) open DIEP flaps. Robotic flaps were harvested in multiport

TAP fashion with novel port placement described with a supra-umbilical camera port and bilateral instrument ports 10 cm from the midline at the corners of the skin incision near the linea semilunaris. This port placement does not require re-docking for contralateral pedicle dissection for bilateral DIEP flaps. Preoperative imaging with CTA was used and criteria for robotic candidacy was <2.5 cm intramuscular pedicle course. Significantly shorter fascial incision was reported 2.7+-1.1cm robotic vs 8.1+-1.7cm open ($p<0.0001$). Robotic time was reported to be 53+-13 cm for pedicle dissection and 22+-3.5 cm for peritoneal closure. Approximately 100 additional minutes of operating time were required for robotic DIEP with approximate cost increase of $3500 in robotic instruments and disposables. 1 minor wound healing complication reported in robotic cohort and 2 minor wound healing complications were reported in the open cohort. Both cohorts had a 3 day ICU admission post-operatively for flap monitoring, before mobilization on hospital day 4. Follow up at 2, 4, and 12 weeks. No statistical difference in pain scores between robotic and open cohorts on hospital day 1-3 [52].

Murariu et al. published a 2024 retrospective cohort study consisting of 46 bilateral robotic DIEP flaps (23 patients) outlining TAP multiport robotic flap harvest technique similar to that described by Tsai. 3 Ports (supraumbilical camera and bilateral instrument ports) were used in conjunction with the first reported use of ICG dye in robotic DIEP for pedicle identifications and dissection. Average fascial incision of 4.1 cm, average pedicle length of 12.8. Average console time of 139 minutes, average OR time of 739 minutes. Average hospital stay of 3.9 days with 90 day follow up. No flap harvest/pedicle injuries occurred, there was one patient that had partial flap necrosis requiring a revision surgery and one patient with an abdominal wound complication. No cases of post-operative hernia or bulging. There were 2 instances where the case was converted to traditional technique, one was due to dense intraperitoneal adhesions preventing safe identification and dissection robotically, and one with a prior hematoma following C-section obscuring the anatomy and requiring traditional dissection on one side. Overall, this study establishes multiport TAP robotic DIEP as a valid technique to minimize fascial incisional length. Authors recommend assistance with a general surgeon for robotic portion until comfortable with robotic pedicle dissection and the novel use of indocyanine green dye (ICG) fluorescence to assist in identification of pedicle vessels [53,54].

Moreira et al. published a 2024 retrospective cohort study evaluating the learning curve for a plastic surgeon compared to robotics certified general surgeon in TAP multiport robotic DIEP pedicle dissection. Using the cumulative sum method, there were 44 flap dissections performed, 27 by the plastic surgeon and 17 by the general surgeon. There was no significant difference in dissection time between the GS (34.8 minutes) and PS (44.6 minutes) ($P = 0.366$). Both surgeons saw a decrease in dissection time with increasing number of cases. Cumulative sum peaked at patient 9 for the PS and patient 5 for the GS, after which dissection time consistently decreased to significantly faster dissection times at the end of the study period. 7 patients had a bilateral procedure where one surgeon performed the dissection on each side, but the sample size was too small to be amenable for meaningful analysis. There were no intra-abdominal injuries, pedicle injuries, conversion to open, flap losses or long-term complications of hernia/bulge after 1 year of follow up. After 10 flap harvests, comparable operative times between plastic and general surgeons were achieved. Overall, this study shows feasibility of robotics in plastic surgery with a short learning curve for robotic training, high level of safety and improved donor site morbidity after approximately 10 cases [55].

Moreira et al. published a 2024 follow-up matched retrospective cohort study to Murariu's study comparing multiport TAPP robotic DIEP to open technique. Forty-seven patients were included (48 standard DIEP flaps, 46 robotic DIEP flaps) with similar patient characteristics and prior abdominal surgical histories. Fascial incision length in the robotic DIEP group was shorter (4.1 vs. 11.7 cm, $p < 0.001$) with no significant difference in pedicle length ($p=0.238$). Mesh reinforcement of the abdominal wall was used in 13/24 standard DIEPs and none in robotic DIEP patients ($p < 0.001$). Operative time was longer in the robotic DIEP cohort (739 vs. 630 minutes, $p = 0.013$), although sub-analysis showed no significant difference in the operative times of the second half of the robotic cohort attributable to robotic experience and learning curve. The average robotic dissection time was 135 minutes, which decreased significantly with the surgeon's experience. There were no intraoperative complications in the robotic cohort. Hospital length of stay was shorter with robotic DIEP, but not statistically significant (3.9 vs. 4.3 days, $p = 0.157$). Overall, the study highlights the viability of robotic DIEP harvest with decreased fascial incision, similar immediate complication rates, decreased need for anterior rectus mesh use, and decreased robotic time with practice [56].

Discussion

Latissimus Dorsi and DIEP are two flaps currently being harvested for breast reconstruction with robotic technology. Various techniques have been described using multiport vs. single port systems, variance of port placement, retraction vs. insufflation, TAP vs. TEP approach. Overall, the majority of literature has been published from single institutions and have found improved cosmesis/patient satisfaction for robotic latissimus harvest with considerably smaller skin incision while retaining similar flap efficacy and complication rates. Robotic technology allows for the possibility of a single axillary incision for robotic nipple sparing mastectomy and reconstruction with ipsilateral LD. For DIEP flaps, robotic harvest has shown consistently smaller fascial incision during pedicle dissection with similar complication rates to the open technique. There is a limited patient population that qualifies for robotic DIEP requiring a short intramuscular perforator course, and 2 maximum perforators. Long-term data for reduction abdominal bulge and hernia has yet to be seen, but preliminary data is promising. Robotic TAP DIEP harvest can also be combined with other robotic intra-abdominal procedures at the same time if needed. The Da Vinci SP (Single Port) system has shown great promise in the TEP DIEP harvest, sparing intra-abdominal complications with small fascial incisions, although has limited approval for use in the US. Overall, robotic flap harvest has been shown to have similar efficacy as traditional techniques, similar immediate complications, improved cosmesis, slightly higher cost, increased operating time that decreases with surgeon experience/learning curve, with long-term complications yet to be seen.

Future advances in robotic reconstructive surgery are likely going to be guided by innovative systems, such as the Da Vinci SP (Single Port) System, Microsure MUSA, MMI Symani microsurgery robotic system, BHS Roboticscope digital microscope. Robotic systems have been used for head and neck reconstruction anastomoses with limited space, peripheral nerve/brachial plexus repair, and with lymphaticovenous bypass procedures for lymphedema treatment [57]. The next forefront in robotic microsurgery/reconstruction is in its infancy with the use of novel systems to perform microsurgery and supermicrosurgery < 1mm on blood vessels, lymphatics, and nerves. The Symani system is starting to be used for these applications with movement scaling 7-20 fold, tremor elimination, robotic technology is advancing to a point where it will outperform even the most skilled surgeons based on physiologic limitations [58-60]. The Symani system has started to be used in Europe over the last few years and has recently gained FDA approval in the US in April 2024. It has been shown to have similar efficacy as hand-sewn anastomoses in emergent hand reconstruction with promising results after a learning curve of 10 cases with 30% increase in speed [61]. The MUSA system has been used for supermicrosurgical lymphaticovenous bypass to treat breast cancer associated lymphedema and shown to be non-inferior to manual bypass at one year follow up [62]. There is great potential for the use of new robotic systems, taking robotic reconstructive surgery to new heights.

Conclusion

Robotic plastic surgery and flap harvesting for breast reconstruction is still in its early stages. There is great promise shown in reducing donor site morbidity, complications, and incision while retaining a similar or improved degree of cosmesis, lower complication rate, and quality for the result at the expense of cost and operative time. The two flaps being used for breast reconstruction robotically are the Latissimus Dorsi and the DIEP flap. The major advantage to the LD is a smaller incision leading to a lower wound complication rate and improved cosmesis. The major advantage of a robotic DIEP is a more precise and less traumatic harvest of the inferior epigastric perforator vessels minimizing the fascial defect, potentially leading to a reduction in hernia and abdominal bulging post-operatively due to preservation of fascia and anterior rectus sheath.

Limitations and Future Directions

There are no standardized training programs for robotic plastic surgery and robotic training is currently not part of the plastic surgery residency curriculum. Robotic flap harvest is not routinely performed on a large scale with multiple techniques, leading to the slow rate of adoption and lack of large scale outcome data. With the benefits of minimally invasive mastectomy and breast reconstruction, the ability for robotic mastectomy and reconstruction is becoming more feasible with the great appeal of single lateral incision nipple sparing mastectomy and LD reconstruction. Robotic DIEP harvest theoretically has a lower risk of abdominal hernia/bulge complications, but long-term data is not yet available. One of the major future directions for robotics in plastic reconstructive surgery is robotic assistance in microsurgical and supermicrosurgical anastomoses with the ability to scale down movement and filter out physiologic human tremors.

Supplementary Materials

No supplementary materials.

Author Contributions

Conceptualization, Richard Baynosa, Joshua MacDavid, Casey Giles.; methodology, Brett Allen, Noama Iftekar, Alexis Knutson; validation, Jarrell Patterson; formal analysis, Brett Allen, Alexis Knutson; investigation, Noama Iftekar, Richard Baynosa.; resources, Brett Allen, Alexis Knutson.; writing—original draft preparation, Brett Allen, Alexis Knutson, Jarrell Patterson; writing—review and editing, Brett Allen, Richard Baynosa.; supervision, Richard Baynosa, Joshua MacDavid.; project administration, Richard Baynosa, Casey Giles. All authors have read and agreed to the published version of the manuscript.”

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Ethical review and approval were waived for this study due to entirety of data and literature reviewed being previously published, publicly available, and no experimentation/procedures were performed involving humans/animals.

Data Availability Statement

Data available in a publicly accessible repository: The original data presented in the study are openly available within the PubMed database at [pubmed.ncbi.nlm.nih.gov]. Individual source reference information is located within the citations of the reference section.

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Conflicts of Interest

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