Modern Innovations in Breast Surgery: Robotic Breast Surgery and Robotic Breast Reconstruction

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KEYWORDS

• Robotic microsurgery • Robotic breast reconstruction • Robotic nipple-sparing mastectomy • Robotic mastectomy • Robotic latissimus flap • Robotic deep inferior epigastric flap • Robodiep

KEY POINTS

- Although there is a learning curve for robotic nipple-sparing mastectomy, this option may decrease nipple-areolar complex necrosis and mastectomy skin flap necrosis compared with traditional nipple-sparing mastectomy.
- Robotic nipple-sparing mastectomy can be combined with either subcutaneous, prepectoral with acellular dermal matrix, or submuscular alloplastic reconstruction as well as autologous reconstruction.
- Robotic harvest of deep inferior epigastric flap pedicle and latissimus muscle flaps is safe and decreases donor site morbidity.
- Robotic microanastomosis in autologous breast reconstruction and lymphedema surgery may provide improved precision through motion scaling and tremor elimination and improved ergonomics compared with traditional microsurgery.

HISTORY

A “robot” was first defined in 1979 by the National Bureau of Standards and the Robot Institute of America as “a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks.”[1] The first robot adapted for use in surgery, the programmable universal machine for assembly 200 (PUMA) was developed by Stanford researcher Victor Scheinman for General Motors in 1978.[2] The PUMA200 consisted of a single arm and computer control monitor. This would go on to be used by a group of radiologists at Memorial Medical Center in Long Beach, California for use in CT-guided brain tumor biopsies.[3] The success of this group encouraged translation in the urology field for the use of the PUMA in prostatectomies in the late 1980s.[4] However, early applications were constrained to fixed targets due to the limitations of an immobile arm.

Government-funded research on robotic applications in surgery was spurred by an initiative to send a human to Mars announced in 1989 by former president George H.W. Bush as well as interest by the US Department of Defense in providing remote wartime medical assistance. NASA began researching applications of remotely controlled surgical instruments to perform emergency surgical procedures on astronauts.[5] Early ideas for robotically controlled surgical gloves evolved to robotic arms.[5] Robotic technology and applications have continued to evolve since the birth of robotics. Modern robotic technology now allows for precise surgical

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control in dynamic environments, allowing for an ever-growing number of applications of this technology.

Robotic technology was applied in the setting of prophylactic nipple-sparing mastectomy (NSM) for breast cancer gene (BRCA) patients in 2016.[6,7] Although criticized for having a steep learning curve, robotic NSM is now regarded as a viable option, which may improve patient outcomes.[8,9] Improved visualization and ergonomics were reported as early advantages of robotic NSM.[6] Robotic NSM has been shown to have superior outcomes in terms of overall complication rates, wound healing complications, and nipple necrosis rates, likely due to decreased traction on the skin and remote incision placement.[6,7,9–11] Patient satisfaction and esthetic outcomes have also been shown to be high with robotic mastectomy, and oncologic safety data are promising.[9,12]

Consensus statements regarding robotic NSM were developed by the Expert Panel from International Endoscopic and Robotic Breast Surgery Symposium in 2019.[13] A summary of their recommendations includes:

- Indications for robotic NSM include:
  - Prophylactic mastectomies
  - Small breast size with Stage II or less tumor (up to 5 cm) and adequate skin-tumor distance on preoperative imaging
  - Stage IIIA tumors with adequate response to neoadjuvant therapy
  - No skin involvement
- Contraindications for robotic NSM include:
  - Large or ptotic breasts due to technical difficulty (relative contraindication)
  - High-anesthetic risk patients (relative contraindication)
  - Pectoralis muscle or chest wall invasion
  - Inflammatory breast cancer
  - Nipple-areolar complex involvement
- Technical considerations:
  - Recommended incision placement is anterior axillary line at the level of the nipple-areolar complex
  - Recommended skin flap development pre-docking with blunt tunneling with scissors and post-docking dissection with monopolar scissors
  - Recommend intraoperative sub-nipple frozen biopsies
  - Standard postoperative drainage
- In the United States, there is currently a multicenter Investigational Device Exemption trial sponsored by Intuitive Surgical in collaboration with the Food and Drug Administration (FDA) to achieve an FDA-approved indication for the Da Vinci robot for robotic NSM.[a] End points include 30-day complications, conversion to open technique, adverse events related to the device, and reconstructive complications. Approval is anticipated.

CURRENT APPLICATIONS OF ROBOTICS IN BREAST RECONSTRUCTION

Alloplastic Reconstruction Following Nipple-Sparing Mastectomy

Background

Immediate reconstruction of the breast may be completed with either autologous tissue or alloplastic devices following robotic NSM.

Patient positioning and robot setup

The patient remains in supine for the duration of the procedure. Placement of the ipsilateral arm over the head is the preferred position for robotic mastectomy and implant-based reconstruction.[13] Alternatively, the arm can be abducted to 90° and secured on an arm board. The robot (da Vinci Surgical System, Intuitive Surgical, Sunnyvale, CA) is positioned at the patient's head. Tumescence solution with epinephrine may be infiltrated into the breast before mastectomy to assist with hemostasis and visualization.[7,11,14] Blue dye may be injected using a hypodermic needle at the borders of the breast to prevent over dissection.[15] A 4 to 4.5 cm incision is made at the anterior axillary line to allow access for both the mastectomy and reconstruction. Our preference is to place this incision at the level of the nipple-areolar complex to allow for unobstructed rotation of the robot with the arm secured on an arm board, whereas more superior incision placement in the axilla can place the arm at risk of injury from the robot (**Fig. 1**). Mastectomy is completed using a single port and 8 mm Hg of insufflation.[6,16] Insufflation allows for uniform doming of the skin without the use of external retractors (**Fig. 2**). The breast tissue is raised first off of the pectoralis muscle, followed by anterior dissection, to allow for easier identification of the end point of superficial dissection.[15]

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[a] Institutions participating in the multicenter Investigational Device Exemption Trial for Nipple Sparing Mastectomy include: University of Texas M.D. Anderson Cancer Center, University of Pennsylvania, Northwell Health, Mayo Clinic Rochester, NorthShore University Health System, and Mayo Clinic Florida.

Fig. 1. Incision and specimen from a robotic nipple-sparing mastectomy.

Operative technique

Following completion of the mastectomy, reconstruction may be completed in either a prepectoral or subpectoral plane. Subpectoral reconstruction proceeds with the development of the subpectoral plane through direct visualization from the lateral chest wall incision. The single-port system is then reintroduced, and insufflation commences. The subpectoral plane is then developed using monopolar scissors. The robot is then undocked and removed. Partial serratus may be elevated under direct visualization for a complete submuscular pocket. A silicone implant sizer is then placed to verify pocket dissection. If pocket revisions are necessary, these may be completed using a lighted surgical light emitting diode (LED) retractor (OBP Surgical, Lawrence, MA). The field is the reprepped, and the silicone implant is placed. The muscle is then reapproximated with sutures using a lighted retractor. Irrigation is performed, and two drains are placed before skin closure.

Subcutaneous implant placement is also possible given the remote incision location if adequate mastectomy flap thickness is preserved. Alternatively, placement of acellular dermal matrix using robotic techniques has been described and is our preferred technique.[17] An implant sizer is placed in the subcutaneous plane, and the implant borders are marked externally on the skin surface to be used as landmarks (**Fig. 3**). Acellular dermal matrix is then trimmed to the appropriate size and contour on the back table for the chosen implant. If a tissue expander has been chosen, it is then placed into the pocket and the robot is used to secure the tabs. The expander is filled with air to the desired volume (**Fig. 4**). Acellular dermal matrix is then introduced into the mastectomy pocket and draped over the expander. The robot is then reintroduced, and external skin markings are palpated by an assistant to guide robotic suturing of the acellular dermal matrix into the appropriate position using a parachute method. Alternatively, for direct-to-implant reconstruction, the acellular dermal matrix is secured into the appropriate position in the pocket first using robot-assisted sutures medially, superiorly, and laterally. The implant is then inserted followed by completion of suturing of the lateral border of the acellular dermal matrix under direct visualization. Pocket control and suturing of the internal mammary fold may also be completed with the robot.

Fig. 2. Robot setup and patient positioning for nipple-sparing mastectomy are shown. The breast is transilluminated which aids with dissection.

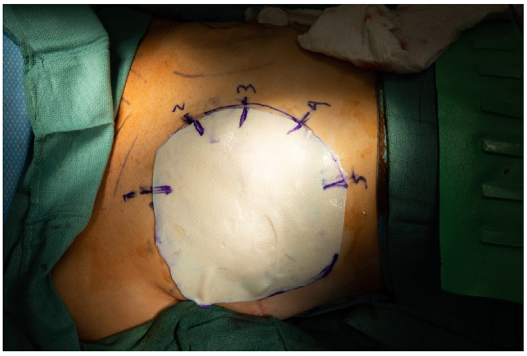

Fig. 3. Acellular dermal matrix inset is planned before insertion.

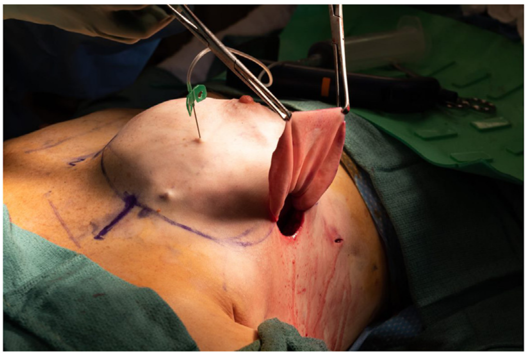

Fig. 4. Tissue expander is place into the mastectomy pocket and inflated to the desired fill volume with air. Acellular dermal matrix (ADM) is draped over the expander and secured in place using the robot using a parachute method.

Robotic Deep Inferior Epigastric Perforator Flap Harvest

Background

As autologous breast reconstruction, with the abdominal donor site as the workhorse, has become the gold standard, efforts have long been directed at reducing donor site morbidity. The evolution of muscle preserving techniques, culminating with the deep inferior epigastric perforator (DIEP) flap, has helped to decrease abdominal wall complications to some extent. However, hernia and bulge remain a concern, with rates of abdominal wall weakness of up to 20% being reported after DIEP flap harvest (**Fig. 5**).[18–22] Although flap dissection using the lateral row perforators results in lower incidences of fat necrosis and a more expedient flap harvest due to a shorter intramuscular course compared with medial row perforators, hernia and bulge weakness is increased due to the sacrifice of motor nerves to the rectus abdominis muscle.[21,23–26]

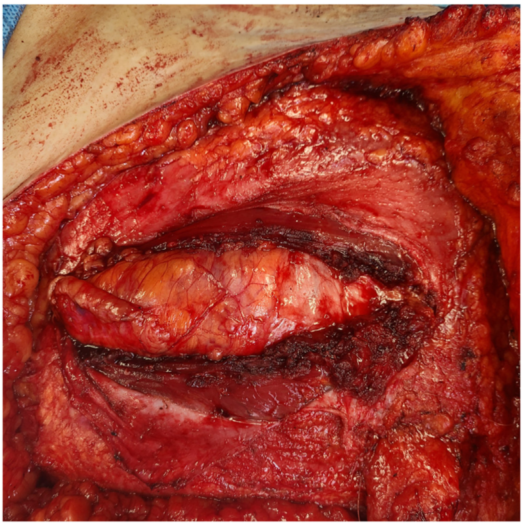

Fig. 5. Fascial incision is shown in a traditional DIEP flap harvest.

Robotic DIEP flap harvest overcomes these challenges by allowing for rapid pedicle harvest from a submuscular approach, allowing for all motor nerves to be spared while limiting the fascial incision. A robotic, intraperitoneal approach to the DIEP flap pedicle harvest was first described by Gundlapalli and colleagues.[27] Initial reports by several centers have been promising for excellent outcomes using the robotic approach to DIEP flap harvest, with no flap losses, intra-abdominal complications, or postoperative hernia/bulge having yet been reported in the literature.[28–31] We recently reported the largest series of intraperitoneal robotic DIEPs to date with no microvascular complications and subjectively improved donor site discomfort.[29] Currently, four major US centers are performing intraperitoneal robotic DIEPS nationally, including MD Anderson, Northwell Health, University of Pittsburgh, and Cleveland Clinic. Other minimally invasive approaches including laparoscopic and extraperitoneal approaches have also been explored with more limited adoption.

Preoperative planning

Preoperative imaging is mandatory for planning for robotic DIEP flap harvest. A computed tomography angiography or magnetic resonance angiography may be performed at the preference of the surgeon. Perforators are identified on imaging. Patients with a single-dominant perforator or two closely grouped perforators with a short intramuscular course are considered candidates for robotic DIEP flap harvest. If multiple perforators or rows are required for harvest, an open approach is used. After identifying target perforators, intramuscular course is determined. A lateral row perforator is selected if possible for a shorter intramuscular course. The intramuscular course is measured and subtracted from the total pedicle length to the external iliac origin to determine the benefit of spared fascial incision length (**Fig. 6**).[32] In appropriate candidates, an average of 9.1 cm of fascial incision benefit has been reported on imaging studies.[33] An estimated 27% of abdominally based flap patients are candidates for robotic flap harvest.[33] This is based on a cutoff of a 4-cm intramuscular course. If indications are expanded to include any patient for whom dissection below the arcuate line can be avoided, the number of eligible patients goes up to 70%. Avoiding dissection below the arcuate line is hypothesized to be the functional cutoff that makes the most

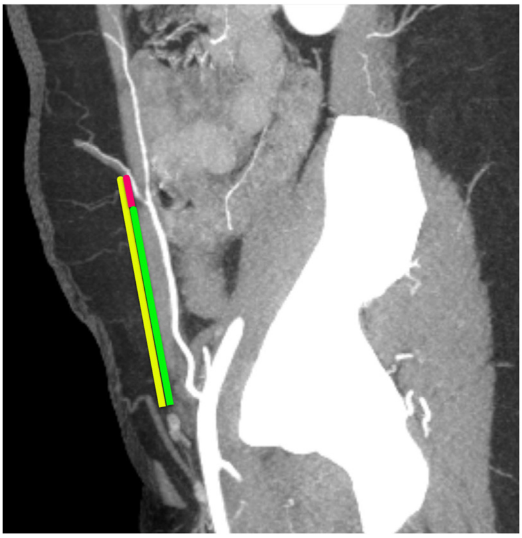

Fig. 6. Sagittal view of deep inferior epigastric CT angiography analysis showing length intramuscular course (*red*), length of pedicle (*yellow*) and derived benefit from subtraction of length of intramuscular course from pedicle length (*green*).

difference in abdominal wall morbidity as the anterior layers of the sheath provide the most structural integrity above the arcuate line.

Patient positioning and robot setup

Standard abdominal flap markings are performed preoperatively. The patient is positioned in a supine position with bilateral arms abducted on arm boards at 90°. The operation begins with standard DIEP flap harvest with flap elevation and isolation on target perforators based on preoperative imaging. Following confirmation of adequate perfusion on chosen perforator(s), the fascia is incised and intramuscular dissection of the perforator is performed. The fascial incision is typically limited to 2 to 4 cm (**Fig. 7**). When the submuscular portion of the pedicle is encountered, the flap is secured and the robot is brought into the operating field. The robot is positioned with arms at 90° at the patient's side, on the ipsilateral side of the flap for unilateral harvest with arms docked across the patient on the contralateral side of the abdomen. For a bilateral harvest, central docking above the umbilicus provides exposure to both DIEP pedicles. A Da Vinci Si or Xi robot system can be used for DIEP flap harvest; however, rotation of the arms on a boom with the Xi allows for completion of bilateral reconstruction without repositioning the robot.

Operative technique

Our preferred method to access the peritoneal cavity is with a Veress insufflation needle technique. An AirSeal port is placed (CONMED, Utica, NY) and pneumoperitoneum established at 10 to 15 mm Hg. A 30° camera scope is placed through the insufflation port. Three 8 mm ports are then placed through the fascia under direct visualization on the contralateral side for unilateral flaps at a line connecting the anterior axillary line and the anterior superior iliac spine (ASIS). The cranial port should be placed inferior to the costal margin and the caudal port superior to the ASIS. The middle port is placed between these two ports. The ports are placed lateral to the semilunar line to maximize the visualization and freedom of movement (**Fig. 8**).

Following docking of the robot, the inferior epigastric pedicle is visualized superficial to the peritoneum. The peritoneum is sharply incised using monopolar scissors and bipolar graspers. Dissection starts near the origin of the pedicle from the external iliac vessels and proceeds to the perforator. When the fascial opening is encountered, gas may leak from this opening

Fig. 7. Length of fascial incision for a periumbilical perforator is shown.

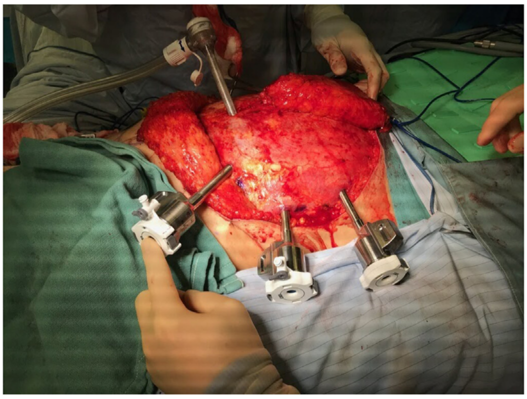

Fig. 8. Port placement for robotic DIEP flap harvest is shown. The patient's head is to the left in the photography. Left DIEP flap harvest is being completed.

and can be controlled by gentle pressure with a moist lap pad by the sterile assistant. When the pedicle is freed, a clip is placed across the origin of the vessels. The pedicle is then divided and removed through the fascial opening (**Fig. 9**). The pneumoperitoneum is then decreased to 8 to 10 mm Hg to allow for a tension-free robotic closure. The posterior rectus sheath is closed with a running barbed suture. Our practice is to complete the peritoneal closure, although the flap is ischemic, as this typically takes less than 15 minutes. Microsurgical anastomosis of the flap then proceeds in typical fashion.

Future directions

Jung and colleagues[34] reported early findings from robotic harvest of the DIEP pedicle in an extraperitoneal plane. They report the use of a da Vinci SP robot (Intuitive Surgical, Sunnyvale, CA). Using a single-port system allowed for access into the narrow preperitoneal potential space and development of a dissection plane. Their early findings are promising, and further experience with this technique is needed. The senior author has used the single-port system in the laboratory for bilateral DIEP harvests from a central, subxiphoid dock and it seems to be smooth and relatively straightforward.[35]

Fig. 9. Pedicle length compared with fascial incision in robotic DIEP flap harvest is shown. Note that the less than 2 cm fascial incision in the bottom left corner of figure. Patient's head is toward the bottom of the photograph.

Robotic-Assisted Microsurgery

Robotic microanastomosis

Some of the earliest reported applications of robotic technology were to perform vascular anastomoses. Robotic coronary artery bypass grafting was first reported in animal models and then successfully applied in human trials with high graft patency rates.[36–39] This was followed by preclinical feasibility studies in microsurgery.[40–43] The first in vivo robotic microanastomosis in plastic surgery was reported by Selber in reconstruction of a floor of mouth defect using an anterolateral thigh flap. The 2-mm arterial vessels were anastomosed end-to-end using Black Diamond robotic needle drivers.[44] Robotic systems allow for magnification with high-definition optics, motion scaling, and tremor elimination, making the applicability to microsurgery appealing. Acquisition of robotic microsurgery skills has been shown to be rapid.[45–47]

If being used in conjunction with a robotic NSM, the thoracodorsal vessels may easily be accessed through the anterior axillary incision for use as recipient vessels. Robotic anastomosis may be completed in this scenario for a uniquely integrated robotic breast reconstruction experience. The robot allows for the completion of microanastomosis in a narrow space and may also be used with DIEP flap reconstruction to internal mammary vessels, allowing for a rib-sparing vessel harvest with excellent pedicle length transposed through a proximal rib opening.[48] Robotic microanastomosis allows for ergonomic operating and may evolve to be the standard for microsurgical technique in the future, especially as robotic systems specialized for microsurgery continue to evolve.[46,49]

Robotic supermicrosurgery

Two things have occurred to push the field of robotic microsurgery forward. One is that surgical robots continue to differentiate into more task-oriented and specific devices. This allows smaller, more compact devices with better optical systems and more extreme motion scaling to have emerged. At the same time, lymphedema surgery and supermicrosurgery have become more important parts of care of the patient with breast cancer. Supermicrosurgery on vessels between 0.2 and 0.8 mm challenges the limits of human physiology. Our operating microscopes have enhanced our vision exponentially, but we have had no such enhancements of our physical movements. Two microsurgical robots have emerged to address supermicrosurgery, specifically treatment and prophylactic lymphovenous bypass. These procedures are technically challenging and in the case of prophylactic lymphovenous bypass are performed at steep angles in the axilla. The MUSA (Microsure, Maastricht, Holland) is one such robot that takes the advantage of existing microsurgical instruments but uses hand controls and allows continuous motion scaling and tremor elimination.[46,50] The SYMANI (MMI, Calci, Italy) has built its own instrumentation based on a massively scaled down version of Intuitive pulley technology.[51] Both of these devices are CE (Conformité Européenne) marked in Europe and should be expected to make landfall in the States. These robots will likely find a place in precision anastomoses in lymphedema and other applications.

Robotic Latissimus Dorsi Pedicled Muscle Flap Reconstruction

Background

Latissimus dorsi pedicled muscle flap for implant coverage remains an option for reconstruction in patients who are not candidates for free tissue transfer or at institutions without microsurgical capabilities. As traditional latissimus muscle harvest requires a lengthy incision for visualization and pedicle isolation, early attempts at improving donor site morbidity through minimally invasive harvest using an endoscope were trialed in the late twentieth century.[52–54] However, this proved to be limited by endoscope rigidity, the curvature of the thoracic cage and the lack of fine movements or multiple degrees of freedom at the instrument tips. The first report of robotic latissimus muscle harvest feasibility in cadavers was published by Selber.[55] A case series including five pedicled latissimus for implant-based breast reconstruction was then reported by Selber and colleagues, [56,57] showing a rapid, shallow learning curve with decreased operative time for flap harvest. Latissimus harvest both in conjunction with robotic NSM and for use in a delayed fashion for robotic implant-based breast reconstruction has since been reported to be safe and with good outcomes and by several groups.[11,58,59]

Patient positioning and robot setup

The latissimus borders are marked preoperatively. The patient is positioned in lateral decubitus, similar to open latissimus muscle flap harvest. A short, vertical incision at the anterior axillary line may be used to access both the mastectomy and latissimus dissection for immediate reconstruction. Alternatively, a previously made axillary or mastectomy incision can be reused when performing delayed reconstruction. Superficial dissection is initiated under direct visualization using monopolar electrocautery and a lighted surgical LED retractor to allow for port placement. The robot is then placed at the side of the table posterior to the patient with the arms aligned in the plane of the muscle and parallel to the floor.

Operative technique

Following superficial dissection, three ports are placed subcutaneously. Ports are placed at 7, 14, and 21 cm from the posterior axillary crease in a line just anterior to the edge of the muscle. Insufflation commences and is set to 10 mm Hg. The dissection of the muscle begins first along the deep surface. This plane is relatively avascular, and insufflation assists with dissection. Monopolar scissors and a grasper are used for dissection, and vessels are mostly cauterized. If particularly large, a vessel can be clipped with robotic clip appliers, but this is rare. The subcutaneous dissection is performed after the superficial dissection is complete to prevent insufflation pressure compressing the muscle against the chest wall during deep dissection. The superficial dissection is completed in a similar manner, and the muscle disinserted from inferior and posterior attachments. The arm may need to be repositioned by an assistant at the inferior and superior extents of the muscle dissection to avoid collisions among the robot arms at the extremes of dissection. The axillary dissection is completed last with division of the tendon, taking care to avoid injury to the pedicle. The robot is then undocked, and the muscle is passed through the access incision. Drains are placed in the donor site through the two lower ports before closure. For patients that require a muscle only latissimus for breast reconstruction, the robotic approach offers a minimally invasive technique that is reliable and safe. Indications are mostly for patients who had good expansion despite postmastectomy radiation, but whose overlying skin would be jeopardized by a proper capsulectomy and implant placement, making a vascularized muscle layer valuable. It is inset and serves a similar function to ADM; only it carries a robust blood supply and has better excursion and lower pole support than the pectoralis.

Robotic applications to breast-conserving therapy

A pedicled latissimus muscle flap has also been described as a safe option for the reconstruction of segmental mastectomy defects in patients with low breast volume or high relative tumor size to breast volume.[60] Robotic harvest of the latissimus muscle flap may also be applied safely for this application. Lai and colleagues[61] have described excellent outcomes using a robotic latissimus to preserve breast volume in oncoplastic reconstruction.

DISCUSSION

Several applications of robotic surgery exist both in breast surgery and plastic and reconstructive surgery. However, at this time, US FDA approval has not yet been obtained for robotic mastectomy or for any plastic surgery applications of robotic surgery. Therefore, all applications are currently considered off-label. Robotic mastectomy and reconstructive surgery have been shown to be safe and viable options. A 501(k) FDA approval prospective safety and outcomes study of robotic latissimus harvest was recently published by our group.[62]

SUMMARY

Robotic surgery allows for minimal access incisions and decreased donor site morbidity in breast surgery and breast reconstruction. Although a learning curve exists for use of this technology, it can be safely applied with careful preoperative planning. Robotic NSM may be combined with either robotic alloplastic or autologous reconstruction in the appropriate patient.

CLINICS CARE POINTS

- Ensure safe positioning of the arms during robotic breast surgery to avoid neurovascular injury and impingement from the robot.
- Carefully plan both incision placements and port placements to maximize access to surgical areas and robotic camera view.
- It is easier to become disoriented with breast borders during robotic mastectomy and acellular dermal matrix parachute suturing; therefore, attention to marking of breast borders and planning is necessary.
- The standard use of drains is recommended for robotic flap donor sites and mastectomy sites.
- Preoperative imaging is mandatory to determine which patients will benefit from robotic deep inferior epigastric perforator flap harvest through evaluating the potential fascial benefit by subtracting the intramuscular length from the total pedicle length.
- A pedicle latissimus muscle flap may be used in breast reconstruction for implant coverage or for reconstruction of breast conserving therapy defects in patients with small breasts

DISCLOSURE

The authors have no disclosures. No funding was received for completion of this article.

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