Workhorse Flaps in Chest Wall Reconstruction: The Pectoralis Major, Latissimus Dorsi, and Rectus Abdominis Flaps

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ABSTRACT

Large and life-threatening thoracic cage defects can result from the treatment of traumatic injuries, tumors, infection, congenital anomalies, and radiation injury and require prompt reconstruction to restore respiratory function and soft tissue closure. Important factors for consideration are coverage with healthy tissue to heal a wound, the potential alteration in respiratory mechanics created by large extirpations or nonhealing thoracic wounds, and the need for immediate coverage for vital structures. The choice of technique depends on the size and extent of the defect, its location, and donor site availability with consideration to previous thoracic or abdominal operations. The focus of this article is specifically to describe the use of the pectoralis major, latissimus dorsi, and rectus abdominis muscle flaps for reconstruction of thoracic defects, as these are the workhorse flaps commonly used for chest wall reconstruction.

KEYWORDS: Chest wall reconstruction, flap, latissimus dorsi, pectoralis major, rectus abdominis, sternal osteomyelitis

Reconstruction of chest wall defects is a challenge characterized by the fundamentals of reconstructive surgery: the restoration of form and function. The choice of reconstructive technique requires the surgeon to understand both the anatomic and physiologic morbidity related to the defect. Important factors for consideration are coverage with healthy tissue to heal a wound, the potential alteration in respiratory mechanics created by large extirpations or nonhealing thoracic wounds, and the need for immediate coverage for vital structures. The vast majority of large and life-threatening thoracic cage defects typically result from the

treatment of traumatic injuries, tumors, or infection. Congenital anomalies and radiation injury are also other common etiologies.

PRINCIPLES OF RECONSTRUCTION AND TECHNIQUE SELECTION

In general, the primary goals of chest wall reconstruction are usually one or more of the following:

1. Stabilization of thoracic skeletal defects that might alter respiratory mechanics.

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2. Obliteration of intrathoracic dead space that may otherwise promote ongoing sepsis.
3. The protection of vital intrathoracic structures or suture lines.
4. Soft tissue coverage of large soft tissue defects external to the thoracic cage.

Skeletal reconstruction may be necessary depending on the size of the defect. The extent of the defect is often measured by the number of ribs resected. Several authors have evaluated the extent of skeletal defects and the requirement for skeletal stabilization using this parameter. The absolute requirement for restoration of skeletal continuity is controversial; however, a common practice that is generally upheld in the literature is to accept resection of two contiguous ribs and to provide skeletal support with prosthetic material after resection of three or more contiguous ribs.

When skeletal stability has not been compromised by the resection, and if vital structures are not exposed, a combination of skin grafts, local skin flaps, and negative-pressure wound therapy may be the most expeditious or least morbid procedures and will often suffice. Prior chest wall irradiation and chronic infection are specific situations that may preclude the use of these techniques in light of a high failure rate, and a more complex reconstruction with non-irradiated muscle or myocutaneous flaps should be considered early. Larger defects that expose vital structures or conditions that require dead space to be filled (such as chronic empyema or bronchopleural fistula) also call for larger musculocutaneous or muscle flaps to be used. The choice of technique depends on the size and extent of the defect, its location, and donor site availability with consideration to previous thoracic or abdominal operations.

Several authors have presented algorithms for reconstruction of the chest wall.^{1,2} As in most reconstructive practices, algorithms may be useful in smaller defects or certain commonly encountered situations; however, they can be difficult to apply in some cases due to the complexity and variety of defects and pathologies encountered. The reconstructive surgeon should have a wide spectrum of techniques in his or her armamentarium and be ready to alter the preoperative plan based on intraoperative findings.

The focus of this article is specifically to describe the use of the pectoralis major, latissimus dorsi, and rectus abdominis muscle flaps for chest wall reconstruction, as these are the workhorse flaps for chest wall reconstruction.

HISTORICAL PERSPECTIVE

Tansini is consistently credited with the first use of a muscle flap in chest wall reconstruction with his account of anterior chest wall coverage using the latissimus dorsi

after radical mastectomy in 1906. Further reports of latissimus transpositions for anterior chest wall defects were described in the 1940s and 1950s; however, the technique did not gain traction until interest in muscle and musculocutaneous flaps was revived in the 1970s and is now routinely practiced. Additionally, major surgical and technological advances around that time popularized the practice of open heart and major thoracic surgery as safe and routine procedures. As well, radiation therapy became a more prevalent treatment modality for breast, chest wall, and lung pathologies, albeit with an inevitable complication rate.

Several authors have since made significant contributions to chest wall reconstruction with innumerable techniques described, encompassing the whole reconstructive spectrum from skin grafting to microvascular free tissue transfer, native bone reconstruction, prosthetic implants, and negative-pressure wound therapy. Accordingly, the pectoralis major, latissimus dorsi, and rectus abdominis have emerged as the three workhorse muscle flaps most commonly used in reconstruction of chest wall defects. These flaps are robust and reliable, have a consistent vascular anatomy, and have versatility to cover small or large defects and potential to include overlying skin paddles.

PECTORALIS MAJOR FLAP

Muscle Anatomy

The pectoralis major is one of the four anterior muscles that attach the pectoral girdle to the anterior chest wall, along with pectoralis minor (deep), serratus anterior (inferiorly), and subclavius (superiorly). Its origin is twofold: a clavicular head originating from the anterior medial half of the clavicle, and a sternal head originating from the anterior manubrium, sternum, and costal cartilages 1 to 6 as well as the external oblique aponeurosis. These two heads are separated by a groove but converge laterally to form a single wide tendon that inserts laterally on the intertubercular groove of the proximal humerus, facilitating internal rotation and adduction of the humerus. The lateral edge of the muscle forms the anterior axillary fold and the anterior wall of the axilla.

Vascular Anatomy

The pectoralis major muscle is supplied by one dominant vascular pedicle (thoracoacromial artery) and several secondary pedicles consistent with a Mathes and Nahai type V muscle flap. The medial and lateral pectoral nerves accompanying the pedicle provide motor innervation. The thoracoacromial artery provides the dominant axial supply to the pectoralis major and originates from the second part of the axillary artery, directly deep to pectoralis minor, and courses laterally. This is a

consistent and reliable pedicle on which the whole muscle can be raised without disrupting the underlying pectoralis minor. Detailed knowledge of the thoracoacromial artery vascular anatomy is useful in maximizing pedicle length and the arc of rotation or transposition of the muscle and if a portion of the muscle has been resected for the extirpation.

The thoracoacromial artery divides into four branches as it pierces the clavipectoral fascia: clavicular, pectoral, acromial, and humeral branches. The dominant branch to the sternocostal portion is the pectoral branch, and although this originates from the main trunk (lateral to pectoralis minor), it courses under pectoralis minor and pierces the clavipectoral fascia medial to its tendon. It then runs on the deep surface of the pectoralis major before giving rise to muscular branches as well as cutaneous perforators that supply the skin overlying the ipsilateral hemithorax.

The clavicular branch arises from the thoracoacromial trunk lateral to pectoralis minor and has a much shorter pedicle (1 cm) before it pierces the clavipectoral fascia and runs on the undersurface of the clavicular portion of the muscle. It almost exclusively supplies the clavicular head, subclavius muscle, and the soft tissues around the clavicle.

The muscle also has reliable secondary pedicles most importantly from the internal mammary artery. The internal mammary artery gives rise to important perforating branches that pass through the intercostal spaces ~1 to 2 cm lateral to the sternal edge. Most commonly, three perforators exist that enter the pectoralis via intercostal spaces 1, 2, and 3, and the second perforator is usually the largest. Preserving these perforators allows a medially based turnover flap to be used for sternal coverage.

The majority of the muscle's venous drainage is achieved by venae comitantes associated with the pectoral branch of the thoracoacromial artery ultimately draining into the axillary vein. The overlying skin drains through venules accompanying arterial perforators. The cephalic vein also receives tributaries draining from the overlying skin paddle but does not form part of the pectoralis muscle's venous drainage.

Harvest Technique

The surface markings of the muscle are easily identified with the clavicle superiorly, sternum medially, and the anterior axillary fold laterally. The pedicle originates from the axillary artery at the midpoint of the clavicle and heads inferiorly before arcing medially to follow a line drawn from the acromion process to the xiphoid.

In chest wall reconstruction, the pectoralis flap is most commonly used as a muscle advancement or rotation flap based on the thoracoacromial pedicle (Fig. 1, Fig. 2). It can be used as a musculocutaneous

or even osteomusculocutaneous flap although this is not usually necessary.

ROTATION-ADVANCEMENT FLAP

Most commonly, the pectoralis major (PM) muscle flap is used to cover dehiscence or debrided median sternotomy wounds, and as such is typically accessed via this same incision. After raising minimal subcutaneous flaps off the surface of the muscle, the muscle is elevated off the chest wall from medial to lateral, taking care to ligate the intercostals and internal mammary perforators medially. It is important to leave some perforators from the pectoralis muscle to the overlying skin to maximize healing potential of the midline and to minimize the risk of seroma. Care is also taken to avoid elevating the pectoralis minor with the flap. The muscle's insertions on the rectus abdominis and external oblique inferiorly are divided, and the flap is elevated superolaterally exposing the pedicle. This dissection is often sufficient to advance the flap medially to cover sternotomy defects. Additional mobility can be achieved by detaching the sternocostal head from the clavicular head of the muscle by developing the groove between the muscles or releasing the clavicular attachments. If necessary, the humeral insertion of the muscle can be released laterally, although this usually accentuates the aesthetic distortion of the anterior axillary. This can be done through a separate incision near the humeral insertion. When a significant amount of mediastinal dead space is a problem, bilateral flaps are usually necessary.

ALTERNATIVE CONFIGURATIONS

Pectoralis major turnover flaps can be used, especially in clinical situations where the inferior pole of the sternal wound requires coverage. These flaps are based medially on the secondary blood supply to the pectoralis major muscle, the internal mammary branches. If the left internal mammary artery was harvested for a cardiac bypass procedure, only the right pectoralis turnover flap can be used. After the subcutaneous dissection has exposed the anterior fascia of the PM, a counterincision can be made laterally, and the pectoralis tendon is divided. The submuscular dissection then proceeds from superolateral in a medial direction raising the pectoralis off the thoracic cage and pectoralis minor. The dissection continues until the internal mammary branches are identified medially, usually ~1 to 2 cm lateral to the sternum. In the traditional medial turnover technique, the thoracoacromial pedicle is divided as it enters the undersurface of the muscle laterally. Disadvantages to the turnover flaps include the use of the secondary blood supply; large subcutaneous flaps must be raised on the chest wall; and secondary median sternotomy will devascularize the muscle closure.

Nahai has described an alternative turnover technique that can be used to minimize donor site morbidity, where the thoracoacromial pedicle is identified and

Figure 1 (A) A 37-year-old man with a full-thickness chest wall defect after multiple debridements of left sternoclavicular joint sepsis. (B) Left pectoralis major muscle has been harvested based on the thoracoacromial pedicle and rotated superiorly. (C, D) Left pectoralis muscle flap after inseting and skin grafting.

Figure 2 A 77-year-old woman underwent aortic arch replacement complicated by multiple reoperations and a prolonged open mediastinum. (A) Prominent sternal wires after delayed chest closure. (B) Left pectoralis major muscle raised on thoracoacromial pedicle. (C) After disinsertion from the humerus, this easily reaches over the median sternotomy. (D) A similar procedure was performed on the right for additional coverage.

preserved, and the PM is divided just medial to it. The medial portion of the PM is used as a turnover flap based on the internal mammary artery (IMA) perforators. The humeral insertion and anterior axillary fold are preserved, and function is preserved by anchoring the lateral portion of the muscle to the chest wall.

Further muscle splitting modifications have been described by several authors in an attempt to preserve pectoralis function, although they are typically only useful in smaller defects.

Common Clinical Situations

The arc of rotation of the pectoralis major based on the thoracoacromial axis allows the flap to be used in coverage of central chest wounds, supraclavicular defects, and axillary and lateral chest wall defects or the muscle to be transposed to an intrathoracic position for obliteration of dead space. However, the pectoralis major flap is most commonly used to cover anterior chest wall defects in the upper part of the chest, classically wounds resulting from an infected median sternotomy for open heart surgery.

Superficial infections that do not involve the sternum should be treated early by local debridement and dressing changes. Deep infections involving the sternum and mediastinitis are infrequent but life-threatening complications, occurring in 1 to 3% of cases,³ and historically were associated with a mortality of up to 50%.⁴ The most common organisms isolated are gram-positive cocci, *Staphylococcus epidermidis* and *Staphylococcus aureus* however, mixed infections including gram-negative organisms can be involved in up to 40% of cases. Presentation can be florid with sternal drainage, dehiscence, and sepsis or more subtle with only fever, leukocytosis, and sternal pain and instability; however, once deep sternal infection has been diagnosed, conservative management is risky, and an aggressive operative approach is recommended. If diagnosis is delayed, patients may require sternectomy, several trips to the operating room for repeat debridements until the wound appears clean and viable, after which muscle flap reconstruction is recommended. With this approach, mortality is dramatically improved although it still remains 5 to 10%.⁵

In deep wound infections without a significant mediastinal void where only coverage is required, a unilateral PM advancement flap may be enough, although the chest wall skin may need to be elevated off the contralateral PM to facilitate skin closure. In more extensive defects such as in patients who have undergone sternectomy for chronic osteomyelitis, bilateral innervated muscle flaps can be used to provide excellent midline coverage, and without dividing the humeral insertion, function can be well preserved.⁶ This technique also allows for repeat procedures to be performed through the midline at a later date, including further debridements, costochondral resections, or re-

peat cardiothoracic procedures, without sacrificing the viability of the reconstruction.

Disadvantages and Contraindications

Although the pectoralis major myocutaneous flap (PMMF) is ideally suited to vertical central chest defects, not infrequently these wounds extend inferior to the xiphoid process and into the epigastrium. Low sternal and xiphoid defects may be out of reach for the pectoralis flap; Hallock has reported his technique of addressing this issue using a pectoralis major muscle extended island flap, skeletonizing the pedicle in 18 patients with good success.⁷ Advancement of the anterior rectus sheath to the midline in continuity with the pectoralis flap or alternative coverage such as the rectus abdominis flap should also be considered.⁸

LATISSIMUS DORSI FLAP

The latissimus dorsi flap is one of the true workhorse flaps in general reconstructive surgery. Owing to its large potential size, possibility for incorporating multiple tissue types, relatively long pedicle and robust vessels, it is arguably one of the most versatile flaps suited for chest reconstruction. Originally described by Tansini for coverage of large mastectomy defects, Olivari subsequently popularized it for coverage of large radiation-induced wounds of the chest wall.^{9,10} It is now commonly used for coverage of both extrathoracic defects as a musculocutaneous flap and intrathoracic defects to obliterate dead space as a muscle-only flap.¹¹⁻¹³

Muscle Anatomy

The latissimus dorsi is the broadest of the back muscles and accordingly has multiple origins, most importantly the spinous processes of T7 to T12, the thoracolumbar fascia, and the posterior third of the iliac crest. There are also muscular slips that arise from the lowest four ribs, external oblique, and the scapula. Superomedially, it is somewhat covered by trapezius, but otherwise is the most superficial muscle in the back lying directly on the paraspinal muscles medially and serratus anterior more laterally. The large flat belly of the muscle is thinner inferiorly and gains some thickness as it converges into a single broad tendon that wraps laterally around teres major forming the posterior axillary fold to insert medially into the intertubercular groove of the humerus. When harvested completely, the muscle flap can measure up to 20 × 35 cm, with a skin paddle as large as 12 × 20 cm.

Vascular Anatomy

The latissimus is a type V muscle, and its vascular anatomy is almost a mirror image of the pectoralis flap.

The dominant pedicle is the thoracodorsal artery, a terminal branch of the subscapular artery that itself arises from the third portion of the axillary artery. Anatomic variations of the subscapular axis are well described and not uncommon, and in ~2 to 5% of cases, the thoracodorsal artery itself arises from the axillary artery directly.¹⁴ In the majority of cases, before the thoracodorsal artery enters the latissimus, it gives rise to several 1- to 2-mm branches that supply serratus anterior, which can be used to elevate a chimeric flap for broader coverage. After entering the underside of the muscle, the main pedicle divides into two main branches: an upper horizontal branch that travels medially along the superior border of the muscle, and a descending oblique branch that runs inferiorly, parallel to the anterior border of the muscle ~2.5 cm from the edge. The bifurcation is predictably found ~4 cm distal to the inferior scapular border and 2.5 cm medial to the lateral free margin of the muscle.¹⁵ This consistent vascular anatomy allows for a partial latissimus to be harvested when this might be sufficient, minimizing donor morbidity.^{16,17}

Secondary pedicles arise dorsally and mostly perfuse the distal part of the muscle. They are typically found ~5 to 10 cm lateral to the spinous processes and are arranged in a medial row (branches of the lumbar arteries) and a lateral row (branches of the intercostal arteries). The largest and most constant of these are the branches of the 8th to 11th intercostal arteries, however they are typically not useful for large anterior chest wall reconstructions due to their location and short pedicle length. These branches can be used, however, when the latissimus has been previously transected in a standard non-muscle-sparing thoracotomy incision, as the distal portion of the muscle can still be mobilized to provide coverage of limited posterior defects.

Harvest Technique

The inferior tip of the scapula, the superior and lateral borders of the muscle, the spine, and the iliac crest should be marked preoperatively. Optimal positioning for latissimus dorsi (LD) flap harvesting is typically the lateral decubitus position, with the arm prepped and the shoulder flexed to 90 degrees. This corresponds with the preferred positioning for a standard thoracotomy allowing posterolateral and intrathoracic reconstructions to be completed without the need for patient repositioning after flap harvest. For more anterior defects, the latissimus is harvested in this position, and the donor site can be closed prior to repositioning the patient and inseting the flap anteriorly.

The axis and length of the thoracodorsal pedicle afford this flap an excellent arc of rotation, and virtually any part the ipsilateral chest wall can be reached. The most common uses of the LD in chest reconstruction are

as a muscle-only flap for intrathoracic obliteration of dead space or as a musculocutaneous flap for coverage of large chest wall defects resulting from tumor extirpations, infection, or radiation-induced injury (Fig. 3).

SKIN PADDLE DESIGN

In a cadaveric study looking at the location of musculocutaneous perforators larger than 0.5 mm, ~56% of perforators originated from the descending branch, along the anterior edge of the muscle, and the remaining 44% originated from the horizontal branch along the superior border of the muscle. All perforators were located within 8 cm from the bifurcation of the thoracodorsal artery. As such, the skin paddle is usually designed along one of these two axes, in the upper two-thirds of the muscle to maximize the number of perforators included. The thoracodorsal pedicle originates ~2 cm inferior to the pectorohumeral junction, and this point can be used to define the arc of rotation of the skin paddle. A template can be used to transpose the shape of the defect and design a skin paddle at a similar distance from this point, onto the skin overlying the latissimus. Skin islands up to 20 × 35 cm have been described, however donor sites greater than 8 or 9 cm wide will require skin grafting.

Depending on the design of the skin paddle, it may be easier to make the first incision separately, along the anterior edge of the latissimus, in the posterior axillary fold, and identify the pedicle proximally before incising around the skin paddle. Alternatively, the skin paddle incision can often serve as the only skin incision required. The subcutaneous dissection continues posteriorly as far as the midline, inferiorly toward the iliac crest, and superiorly until the upper edge of the muscle is identified. The submuscular dissection begins at the anterior free border of the muscle. The muscle is elevated off the underlying serratus with care taken to preserve the vascular branches to serratus, and the dissection continues as far posteriorly and inferiorly as the subcutaneous dissection. The muscle's secondary pedicles will be encountered along the lowest four ribs, and these should be ligated. The muscle is then detached from its inferior and posterior origins and reflected upwards allowing dissection to continue superiorly identifying the pedicle which can be seen entering the underside of the muscle ~10 cm distal to the humeral insertion. The serratus branches can be divided to increase the arc of rotation or the serratus can be included in the dissection if a larger flap is required. For anterior defects, a subcutaneous tunnel is developed between the defect and the axilla, and the flap is transposed through this.

In cases of persistent pleural infection, a muscle-only latissimus flap can be harvested through a prior thoracotomy incision and transposed intrathoracically via a more superior intercostal space to obliterate

Figure 3 (A) A 44-year-old woman underwent resection of a right anterior chest wall radiation-induced sarcoma, including ribs 2 to 4. (B) Continuity of the thoracic skeleton was restored with a 2-mm-thick Gore-Tex (W.L. Gore and Associates, Inc., Flagstaff, AZ) patch. (C–E) Right latissimus dorsi with a 13 × 26 cm skin paddle was rotated anteriorly for soft tissue coverage. (F) Appearance after inset of the flap. (G) Appearance 3 weeks postoperatively.

intrathoracic dead space.¹² Traditional thoracotomy incisions sacrifice the latissimus, limiting its use in this situation, when a serratus anterior muscle flap may be a more reliable alternative.¹⁸

Common Clinical Situations

The latissimus muscle and musculocutaneous flaps are ideally suited for reconstruction of large anterior or anterolateral chest wall defects. It is also a useful salvage

flap for previously failed pectoralis major or other muscle flaps that require further debridement. In a review of 50 consecutive patients, Arnold and Pairolero concluded that the key to reconstructing these defects successfully is to be absolutely certain that all ischemic and infected tissue is debrided, regardless of the anticipated reconstruction.¹⁹ This most often would require resection of a portion of the thoracic skeleton (in up to 75% of their patients), exposing vital structures, however without any significant pulmonary compromise.

The latissimus is also suited to closure of posterior thoracic defects. Most commonly these are midline wounds, resulting from neurosurgical or orthopedic intervention in spinal pathology often with

exposed hardware or spinal structures.^{20,21} Spinal and paraspinal defects can be easily closed by advancing bilateral musculocutaneous latissimus flaps toward the posterior midline providing robust coverage of life-threatening wounds, with minimum donor-associated morbidity.

RECTUS ABDOMINIS FLAP

Transfer of the rectus abdominis muscle (RAM) was first clinically described by Mathes to reconstruct an abdominal wall defect and quickly evolved into a technique for reconstruction of infected sternotomy wounds.²⁴ It has since become a popular option for breast reconstruction,

Figure 4 A 67-year-old man with a history of diabetes, smoking, and previous CABG. The patient had sternal dehiscence and drainage and was managed with dressing changes at home. (A) He presented ~6 weeks after CABG with exposed sternal wires and copious purulent drainage. (B) The inferior sternum was necrotic and was debrided. (C, D) A VRAM was harvested based on the right superior epigastric artery and rotated to fill the dead space in the inferior aspect of the chest wall.

Figure 4 (Continued) (E) The patient healed without sequelae (early postoperative photo). (F) Two-month postoperative photo.

and the same techniques can be extrapolated to cover large anterior chest wall defects.

Muscle Anatomy

The rectus abdominis is a type III vertical strap-like muscle extending from its origin on the xiphoid process and the 5th to 8th costal cartilages superiorly, inserting on the anterior surface of the pubic symphysis. It has bilateral bellies that meet in the midline at the linea alba, and each muscle belly is enclosed in a tendinous sheath formed by aponeurotic extensions of the external and internal obliques and the transversus abdominis muscles bilaterally. The muscle is broader superiorly and somewhat tapered toward its insertion inferiorly.

Vascular Anatomy

Mathes and Nahai have classified the rectus abdominis as a type III muscle, supplied by two dominant pedicles: the superior epigastric artery and the deep inferior epigastric artery. The flap can be raised in a variety of configurations as a muscular or musculocutaneous flap based on either of these pedicles.

The deep inferior epigastric artery is a branch of the external iliac artery, arising proximal to the inguinal ligament, and passes superiorly in the preperitoneal layer before entering the rectus sheath at the arcuate line. The artery enters the muscle in its lateral third and consis-

tently divides into lateral and medial branches that then anastomose with the superior epigastric artery, which is a terminal branch of the internal mammary artery running within the posterior rectus sheath. Numerous vascular configurations and refinements have been developed with this flap, however for coverage of chest wall defects, the rectus abdominis flap is most commonly harvested based superiorly on the superior epigastric artery (SEA) either as a muscle or musculocutaneous flap.

As a rotational pedicled flap based on this axis, the flap is most useful for coverage of central and anterior chest wall defects. It is particularly useful in three specific situations: (1) when a large volume of tissue is required centrally (after wide sternal and costochondral debridements), (2) when central tissue loss extends inferiorly to the xiphoid and epigastric areas, and (3) when large anterolateral defects exist but the ipsilateral latissimus is not sufficient or has been sacrificed in a previous posterolateral thoracotomy incision.

Harvest Technique

MUSCLE FLAP

Several skin incisions are described for a muscle-only RAM flap including low transverse, midline, and paramedian. A midline incision gives equal access to both sides and excellent exposure superiorly for manipulation of the pedicle and closure of the fascia; however, a low

transverse incision affords better cosmesis. The subcutaneous tissues are dissected off the anterior rectus sheath, which is then incised longitudinally over the muscle belly. The muscle is bluntly dissected out of its fascial envelope ligating perforating branches and identifying the SEA and deep inferior epigastric artery (DIEA) on its undersurface. The muscle is divided inferiorly at the pubic symphysis and the DIEA is ligated. The flap can then be rotated or turned over to cover central chest defects. The anterior rectus sheath is closed primarily in a standard fashion without tension.

MUSCULOCUTANEOUS FLAPS

Perforators arising from the epigastric arteries supply the majority of the central abdominal skin and subcutaneous fat, allowing the RAM flap to be harvested as a musculocutaneous unit. Perforators arise along both the medial and lateral branches of the DIEA that are continuous with the SEA. The most robust and consistent of these are located periumbilically, thus the flap should be designed to include this region. The skin paddle can be designed transversely (TRAM) or vertically (VRAM), both allowing primary closure of the donor site. The VRAM flap is well suited for long, vertical defects, including those that extend toward the sternal notch, the shoulder or the axilla. TRAM flaps can potentially provide a large amount of bulk depending on the patient's body habitus (Fig. 4).

SKIN PADDLE DESIGN

The VRAM flap is designed as a vertical ellipse centered over the ipsilateral RAM and can extend over the whole length of the muscle, incorporating multiple perforators along the SEA axis. Skin paddles up to 30 cm long and 10 to 15 cm wide can be closed primarily, and the arc of rotation is up to 180 degrees in either direction. The axis of rotation pivots around the entry point of the SEA into the muscle at approximately the level of the costal margin and allows the tip of the flap to reach as far proximally as the manubrium and sternal notch if required. The pedicle can be lengthened for a more superior pivot point by dissecting the SEA proximally toward the IMA, although this is not usually required. The blood supply of the lower abdominal skin has been well studied by many authors, and hence the angiosomes of the TRAM flap have been defined as several zones (I to IV) representing decreasing degrees of vascular reliability. Transversely oriented skin paddles can be placed anywhere along the length of the muscle and based on either the left or right rectus muscle depending on the desired arc of rotation. Placing the skin paddle low allows the final donor site to resemble an aesthetic abdominoplasty, however the superior extent of the flap may be too low to include many of the important periumbilical perforators that will be relied on in the superiorly based flap. Placing the skin paddle too high

leaves a very conspicuous scar and shortens the muscular pedicle.

The technique for elevation of the superiorly based VRAM and TRAM is in principle the same with the exception of the skin incisions. The skin and subcutaneous tissues are elevated off the external oblique from lateral to medial, until the medial and lateral borders of the rectus muscle have been identified. In a TRAM flap, zone III is raised first up to the lateral edge of the ipsilateral rectus, where the largest perforators can be identified. Zone IV is elevated next, and subsequent dissection of zone II off the contralateral rectus allows the anatomic location of the contralateral perforators to be identified. This can aid in identifying the level of the ipsilateral medial umbilical perforators, which are frequently a mirror image. The anterior rectus sheath is then incised to include a strip of anterior rectus sheath fascia protecting the identified musculocutaneous perforators. The remainder of the dissection proceeds in a similar fashion to the previously described muscle-only RAM flap.

The technique for a VRAM includes harvesting a longitudinal strip of anterior fascia that runs the whole length of the skin paddle, with care taken to include the most important perforators in the middle third of the muscle. The arc of rotation for musculocutaneous RAM flaps is similar to that for the muscle flap, however these flaps are most frequently used to reconstruct defects that are not contiguous with the donor site, and a subcutaneous tunnel is usually necessary to allow the skin island to be inset remotely. The anterior rectus sheath is usually closed primarily in both configurations, however depending on the flap design, this may be under moderate tension. Consideration should be given to the use of nonabsorbable suture or mesh repair if undue tension is encountered.

POSTOPERATIVE CARE

Subcutaneous drains are routinely placed in the donor site and should be kept in place until the drain output appears serous and low volume. Closed suction drains are also placed under the flap to prevent or identify hematomas that may threaten the flap's viability. When the thoracic cavity has been entered, thoracostomy tubes are recommended in the early postoperative period to evacuate postoperative effusion and pneumothorax and are typically managed by the thoracic surgery team. Thoracic binders are used occasionally for soft tissue compression. In addition, patients are instructed to limit range of motion exercises to minimize harvested muscle movement.

OUTCOMES

Chest wall reconstruction as a single, encompassing entity involves a wide range of pathologies of varying

complexity and a heterogeneous group of patients with diverse alterations in physiology and anatomy. Undoubtedly, however, the primary end point for evaluating the outcome of any technique is a stable, healed wound, and multiple other parameters should be considered including operative mortality, adjunctive procedures, and technique-specific complication rates. Many studies include analyses of postoperative ventilation requirements, tracheostomy rates, and pulmonary function, and these are unquestionably influenced by the overall surgical approach and reconstructive strategy.

Arnold and Pairolero are credited with the largest single-institution series of chest wall reconstructions, reviewing their personal experiences with 500 chest wall reconstructions performed in an 18-year period at the Mayo Clinic. Four hundred seven patients underwent a total of 611 muscle flaps: 355 pectoralis major, 141 latissimus dorsi, and 115 other flaps including rectus abdominis, serratus anterior, and external oblique flaps. The patients' ages ranged from 1 day to 85 years, and their defects were a result of chest wall resections, infected median sternotomies, radiation-induced necrosis, or a combination. Despite this, the perioperative mortality rate was only 3%, and the requirement for tracheostomy was only 4%. Importantly, 83% of patients had excellent results with a healed, asymptomatic chest wall at the time of last follow-up (average follow-up 57 months). Their experience underscores the feasibility, efficacy, and safety of performing muscle flap reconstructions in patients who typically have significant comorbidities, severe pathology, or critical illness as major obstacles to success.

Several other large series reiterate these results. Chang et al reviewed their 10-year experience of chest wall reconstructions at Memorial Sloan-Kettering Cancer Center, which included 113 patients who underwent a total of 157 musculocutaneous or muscle flap reconstructions for chest wall defects. The most common diagnoses in this group were breast cancer and sarcoma, and the majority of patients (106 of 113) underwent only 1 operation. Only 11% of patients required free tissue transfer, and 85% of cases were completed with only one muscle flap harvested. Only 4% of patients had a partial flap loss, otherwise 84% of patients achieved a stable, healed chest wound without any complications.²

These reports consolidate previous series of individual muscle flap techniques used for chest reconstruction, which grew in large part due to the success of the pectoralis flap in treating infected sternotomy wounds.

The pectoralis major muscle flap was first described by Pickrell in 1947 as a turnover flap in chest wall reconstruction but did not gain widespread acceptance until Arnold and Pairolero's major contributions to chest wall reconstruction in the 1970s and 1980s. They initially described a series of six patients with post coronary artery bypass graft (CABG) mediastinitis, successfully reconstructed with PMMFs after radical debridement,

and later reported long-term follow-up of 100 consecutive cases of sternal wound infections. After a median of four operations, the majority of patients were closed with pectoralis major flaps, with only two perioperative deaths. Infection recurred in 26 patients at a median interval of 5 months after closure, all of who required further procedures. The cause of recurrence was found to be inadequate debridement of infected cartilage (16 of 26) or bone (6 of 26) and retained foreign bodies (4 of 26); however, 92 patients had healed wounds at the time of last follow-up (median 4.2 years). Prior to this, conventional treatment for deep sternal wound infections included debridement by the cardiovascular surgery team, prolonged dressings courses, and eventually closure over an irrigation system, with poor outcomes and reported mortality of 20 to 50%.⁴ Accordingly, 65% of the patients in Arnold's series were patients who had not responded to prior treatment attempts by other surgeons, and thus presented in a delayed fashion. Multiple studies have now reiterated Arnold's success with sternal wounds, and have also showed that earlier involvement of a plastic surgery team allows immediate debridement and one-stage pectoralis muscle flap closure of the chest.

Nahai et al reported a series of 211 consecutive patients with infected sternotomy wounds, treated primarily with muscle flap reconstructions.²⁵ This study followed up on a change in their conventional practice of treating infected sternotomy wounds using multiple debridements, dressings, and catheter irrigation, which was instigated after their previous success with muscle flaps that had been used after conventional treatment had failed.²⁶ A total of 377 flaps were used, including 212 pectoralis major and 145 rectus abdominis flaps, with 65% of closures being accomplished in a one-stage procedure. Flap loss was seen in only 0.8% of cases, and mortality was 5%. Primary healing was achieved in the remaining 94.3%, and the authors provided their unit's treatment guidelines, which proposed the unilateral pectoralis major muscle flap as the primary treatment option for superlative results compared with those of conventional treatments.

More recently, Ascherman et al reported their management of 114 consecutive complicated sternotomy wounds.²⁷ The median time from index operation to referral was 16 days; 94% of patients (104 of 114) underwent immediate debridement and repair of the defect with bilateral musculocutaneous PM flaps. The remaining seven patients were deemed too hemodynamically unstable to tolerate a prolonged operation and underwent delayed closure. Their outcomes were equally good with no intraoperative deaths and a 30-day mortality of 8%. Mediastinitis recurred in a single high-risk, immunocompromised patient who had presented with a substernal infection and 1-year history of a draining sinus due to a retained foreign body and required multiple further operations.

On the basis of these and other studies, whenever possible, immediate debridement of deep sternal wound infections and one-stage reconstruction with muscle flaps is advocated and associated with a decreased morbidity and mortality.^{22,23}

Delay in definitive debridement and closure and the use of prolonged dressings changes and catheter irrigation are associated with worse outcomes. Another factor worth considering and that has been shown to have a significant negative impact on outcomes is prior chest wall irradiation. External beam radiotherapy involving the chest wall is used routinely as an adjunctive treatment in breast and lung cancer and can also be associated with the development of radiation-induced malignancy or chronic chest wall wounds requiring wide resection. Whenever possible, non-irradiated muscle should be used for reconstruction of chest wall defects. Arnold reported 100 cases where irradiated wounds were reconstructed using muscle flaps with an overall complication rate of 25%. Notably, when irradiated muscle was used for the reconstruction ($n = 57$), there was a complete flap failure rate of 14%; however, when non-irradiated muscle was used, no flap failed ($n = 43$).

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