Introduction to Chest Wall Reconstruction: Anatomy and Physiology of the Chest and Indications for Chest Wall Reconstruction

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ABSTRACT

The chest wall functions as a protective cage around the vital organs of the body, and significant disruption of its structure can have dire respiratory and circulatory consequences. The past several decades have seen a marked improvement in the management and reconstruction of complex chest wall defects. Widespread acceptance of muscle and musculocutaneous flaps such as the latissimus dorsi, pectoralis major, serratus anterior, and rectus abdominis has led to a sharp decrease in infections and mortality. Successful reconstructions are dependent upon a detailed knowledge of the functional anatomy and blood supply of the chest and the underlying pathophysiology of a particular disease process. This article will provide an overview of key principles and evidence-based approaches to chest wall reconstruction.

KEYWORDS: Chest wall reconstruction

The complex interplay of 12 paired ribs with the internal and external muscles that compose the chest wall has both a structural and a functional role. The chest wall protects the heart, lungs, and liver, provides a flexible skeletal framework to stabilize the actions of the shoulder and arm, and promotes respiratory movement all while reliably delivering more than 20,000 breaths a day. Chest wall dysfunction is associated with significant morbidity and rapid life-threatening consequences. Management and reconstruction of complex chest wall defects has significantly improved over the past half century with long-term success rates improved from 50% to the current 90 to 99% and hospital stays reduced from an average of 84 days to less than

13 days.¹⁻⁶ A focus on anatomy and blood supply has led to the development of muscle and musculocutaneous flaps and the expanded use of prosthetic materials where appropriate. Knowledge of the functional anatomy and pathophysiology of the chest is essential to the success of the reconstructive chest surgeon. This article focuses on chest anatomy and function, with emphasis on the indications and essential principles of chest wall reconstruction.

The study of the thoracic wall and its muscles, vessels, and nerves has been significantly advanced since the end of the past century by anatomic data and classification.⁷⁻²² The principal indications for chest wall reconstruction are tumor (primary or recurrent),

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infection, radiation injury, and trauma, and the particularly unfortunate patient may have any combination of the above.²³ A thorough knowledge of anatomy is the foundation for a clear operative plan and fallback procedure. We will review the important anatomic considerations that are required for normal chest wall function.

RELEVANT CHEST WALL ANATOMY

Skeleton

The skeleton of the thoracic wall is formed by the spinal column and 12 thoracic vertebrae posteriorly, the sternum anteriorly, and bounded by 12 paired ribs and costal cartilages (Fig. 1).⁷ Within the anterior thorax, the first seven pairs of ribs are attached to the sternum, the 8th through 10th ribs are attached to each other by costal cartilage, and the 11th and 12th ribs remain unattached, or "floating." Their coordinated excursion in the anterior chest allows for full chest expansion. The sternal angle (angle of Louis) is a distinct bony ridge continuous with the second rib and corresponds with the level of bifurcation of the trachea and the upper border of the atria of the heart. The arch design of the ribs allows for mild flexing (greater in children), which may absorb a certain amount of blunt trauma and kinetic energy.

Vasculature

The dominant blood supply to the sternum is provided superiorly by paired internal mammary (or thoracic) arteries that interconnect with the posterior intercostals, the lateral thoracic, the acromio-thoracic, and the transverse cervical arteries (Fig. 2). The internal mammary artery is a branch of the subclavian artery and runs behind the costal cartilages alongside the sternum with one or two venae comitantes. Ventral skin and musculature are also supplied superiorly by collateralization of branches of the subclavian vessels down inferiorly to the deep epigastric arteries. The anatomy of this interconnected system forms the basis for many reconstructive flaps. Cutaneous perforators of these vessels are concentrated around the perimeter of the pectoralis major muscle, the costal margin, and over the interdigitations of the serratus anterior muscle in the midaxillary line.⁸ Marcus described that blood supply to the breast as predominately supplied by the internal mammary artery over the lateral thoracic artery in 68 to 74% of patients.⁹ The largest internal mammary artery perforators are reliably located in the second or third intercostal space and are the blood supply to the internal mammary artery perforator flap.¹⁰⁻¹² The largest angiosome in the torso is supplied by the posterior intercostal arteries.¹³ Kerrigan and Daniel described cutaneous flaps based on the intercostal arteries.¹⁴ They described the

course of the intercostal neurovascular bundle from the aorta to the rectus abdominis muscle divided into four segments: the vertebral, the costal groove, the intermuscular, and the rectus. Dorsal perforators of the posterior intercostal arteries branch from the vertebral segment with an average diameter of 1.5 mm and are the basis for the dorsal intercostal artery perforator flap.¹⁵

Musculature

The muscles of the chest wall are divided into two main groups, inspiratory and expiratory, based on their functional consequence (Fig. 3). Inspiratory muscles (e.g., sternocleidomastoid and scalene muscles) expand chest volume by elevating the superior aspect of the rib cage. Expiratory muscles (e.g., rectus abdominis, internal oblique, and external oblique muscles) decrease lung volumes by constricting the rib cage in a downward motion. Shoulder and arm function are achieved by the many muscles attached to the clavicle, scapula, and humerus. Major muscles pertinent to chest wall reconstruction include the pectoralis major, latissimus dorsi, serratus anterior, trapezius, and the rectus abdominis muscle.

The main workhorse for complex sternal wound closure is the pectoralis major muscle and is a first-line treatment for Pairolero and Arnold advanced type II and type III mediastinal infections.¹⁶⁻²¹ The pectoralis major muscle is a fan-shaped muscle that covers the anterior superior portion of the chest and forms the anterior axillary fold, attaching proximally to the medial half of the clavicle, sternum, and the superior six costal cartilages and distally to the intertubercular groove of the humerus (Fig. 4). The pectoralis muscle is a type V muscle with major blood supply from the thoracoacromial artery and segmental blood supply from the internal mammary artery by way of intercostal perforators. The pectoralis major muscle may be raised either as a muscle or musculocutaneous flap and either as an advancement flap based on the thoracoacromial axis or as a turnover flap based on the internal mammary segmental blood supply.²² The majority of central anterior chest defects may be closed with a single pectoralis major muscle, however bilateral pectoralis muscle or musculocutaneous flaps may be used.

The latissimus dorsi muscle is extensively used in chest wall reconstruction.²³⁻²⁷ The latissimus dorsi muscle is a large flap, type V muscle with its anterior two-thirds supplied by the thoracodorsal artery and vein and posteriorly a segmental blood supply based on the intercostal perforators (Fig. 5). The blood supply is derived from the axillary artery, which gives off the subscapular circumflex artery and continues to become the thoracodorsal artery. Nerve supply is by the thoracodorsal nerve. The muscle extends from the lower six

Figure 1 The thoracic skeleton: (A) anterior view, (B) posterior view. (From THIEME Atlas of Anatomy, General Anatomy and Musculoskeletal System, © Thieme 2005, Illustration by Karl Wesker.)

Figure 2 Anterior trunk wall nerves and vessels. (From THIEME Atlas of Anatomy, General Anatomy and Musculoskeletal System, © Thieme 2005, Illustration by Karl Wesker.)

thoracic vertebrae, the crest of the ileum, and wraps around anterosuperiorly to attach to the intertubercular sulcus of the humerus to form the posterior axillary fold with the teres major muscle. The arc of rotation of the latissimus dorsi makes it suitable for spinal coverage and humeral defects, and even in cases without a usable pectoralis major muscle, the latissimus can reach the median chest and sternotomy wounds.²⁸

The serratus anterior muscle is classified as a type II muscle flap and receives blood supply from the lateral

thoracic artery and branches of the subscapular thoracodorsal artery (Fig. 6). The thoracodorsal artery gives branches off to the serratus anterior before terminating in the latissimus dorsi muscle. The main arterial branch to the serratus anterior arises 3 to 6 cm cephalad to the neurovascular leash of the latissimus dorsi muscle.²⁹ In cadaver dissections, Bartlett et al found one (54%), two (44%), or three (2%) branch patterns.³⁰ The muscle averages 10 × 20 cm and spans from the lateral surfaces of the first eight ribs to the medial border of the scapula.

Figure 3 Muscles of the chest wall: (A) anterior view, (B) posterior view. (From THIEME Atlas of Anatomy, General Anatomy and Musculoskeletal System, © Thieme 2005, Illustration by Karl Wesker.)

The serratus muscle acts to abduct and flex the shoulder and holds the scapula against the rib cage. The lateral thoracic artery enters the muscle cephalad on its anterior surface and gives off multiple small branches to individual slips of muscle. The serratus anterior may be raised on a vascular pedicle up to 11 cm giving it an arc of rotation that can reach the anterior chest wall and neck and is an excellent option for intrathoracic defects.³¹ The serratus muscle may also be raised with vascularized rib for composite chest wall defects.³²

The rectus abdominis muscle is a type III, broad vertical muscle of the abdominal wall originating from the pubic symphysis and inserting on the xiphoid process and fifth to seventh costal cartilages (Fig. 7). Blood supply is derived from the superior and inferior deep epigastric arteries. The rectus abdominis muscle may be pedicled superiorly in the absence of the internal mammary system by the additional blood supply from the eighth subcostal artery³³ and can easily cover the lower third of the sternum but can also reach as high as the sternal notch.³⁴

The external oblique muscle originates from the bottom edge of the 6th through 12th ribs and fans out to insert upon the iliac crest, the linea alba, and the pubic and inguinal ligaments (Fig. 8). Innervation is from the

inferior six intercostal nerves, and blood supply primarily derives from the anterior and collateral branches of the posterior intercostal arteries in the 10th and 11th intercostal spaces.^{35–37} The external oblique muscle flap is capable of reaching the third ipsilateral rib space superiorly and up to 5 cm beyond the midline, and elevation of an extended muscle flap may close defects up to 500 cm².³⁸

PHYSIOLOGY OF THE CHEST

The inspiratory and expiratory muscles of the rib cage work in a precisely coordinated movement to execute a functional breath. In the pleural cavity, the lung remains in an inflated state by mechanical coupling of the chest wall and the lung. The work of breathing is minimized by mesothelial cells with microvilli that are enmeshed in hyaluronic acid-rich lubricants.³⁹ Elevated movement of the ribs leads to forced inspiration by increasing the dimensions of the chest through a “bucket-handle” motion and by elevation of the sternum through a “pump-handle” motion.

The muscles of inspiration work actively to create a reduced intrapleural pressure to induce inhalation.⁴⁰ Because of its distinctive curved geometry and specialized

Figure 4 Pectoralis major muscle. (From THIEME Atlas of Anatomy, General Anatomy and Musculoskeletal System, © Thieme 2005, Illustration by Karl Wesker.)

metabolic demands, the diaphragm is the most important respiratory muscle.⁴¹ With assistance from the external intercostal muscles, the diaphragm contracts during inspiration to enlarge the thoracic cavity. Paired sternocleidomastoids and scalene muscles act as secondary accessory muscles to aid in raising the sternum and elevating the upper ribs.

Upon relaxation of the diaphragm, the elastic recoil of the lung in addition to contraction of the abdominal muscles leads to passive expiration. Pulmonary function tests measure forced expiratory volume in 1 second (FEV1), tidal volume, and the ratio of FEV1 to forced vital capacity ratio to quantify this process.

The pathophysiology of lung disease may be broadly classified into either obstructive or restrictive disease. Obstructive processes involve the impediment of expiration by obstruction of the bronchioles and bronchi.

This results in air trapping, and pulmonary function tests may demonstrate increases in functional residual capacity and residual volume with concomitant decrease in FEV1 and vital capacity. Interstitial pathology may cause lung tissue to become less compliant resulting in restrictive lung disease. This is manifested by reduced lung volumes.

Trauma and the ablation of large oncologic defects may require the resection of multiple ribs leading to disruption of chest wall integrity and paradoxical chest movement, a condition known as flail chest. When a flail segment, usually 5 cm or greater in diameter, loses continuity with the surrounding chest wall, ventilation becomes progressively inefficient. Variations include posterior flail segments, anterior flail segments, and sternal flail with fracture of bilateral anterior ribs.⁴² The segment requires adequate fixation to restore normal respiratory physiology. Chest wall

Figure 5 Latissimus dorsi muscle. (From THIEME Atlas of Anatomy, General Anatomy and Musculoskeletal System, © Thieme 2005, Illustration by Karl Wesker.)

defects, depending on their size, may be amendable to either a soft tissue or bony reconstruction. Soft tissue reconstruction is appropriate for two-rib and some three-rib (< 5cm in diameter) segmental loss without functional consequence.^{43–45} Surgical stabilization has been shown to decrease mechanical ventilator days, improve long-term outcome, and lower cost of hospitalization in select patients.^{46,47} Note that restoration of chest wall integrity after reconstruction may not restore lung function if underlying pathology such as significant lung contusion is not addressed.

INDICATIONS FOR CHEST WALL RECONSTRUCTION

Common indications for chest wall reconstruction include infection, congenital abnormalities, tumor ablation (primary or recurrent), radiation injury, and trauma. Infection may manifest itself as mediastinitis or empyema. Sternal wound infection after cardiac

surgery occurs in approximately 0.5 to 9% of cases. Major risk factors for sternal dehiscence and subsequent infection are obesity, diabetes, chronic obstructive pulmonary disease (COPD), and bilateral harvest of internal mammary arteries.⁴⁸ Treatment of sternal infection and dehiscence is radical debridement of all infected tissue, culture-directed antibiotic therapy, and obliteration of dead space.^{49,50} In addition, chest reconstruction with vascularized tissue, most commonly pectoralis myocutaneous advancement, rectus abdominus myocutaneous and other flap procedures such as latissimus dorsi or omentum,^{51,52} have proved to be effective treatments and have lowered mortality rates in patients.

Paolero and Arnold classified sternal wounds based on timing of presentation of infection.⁵³ Type I wounds occur in the first few days postoperatively. These wounds may contain incisional dehiscence with serosanguineous discharge and/or sternal instability. Type II wounds occur in the first several weeks and may present

Figure 6 Serratus anterior muscle. (From THIEME Atlas of Anatomy, General Anatomy and Musculoskeletal System, © Thieme 2005, Illustration by Karl Wesker.)

with cellulitis, mediastinal purulence, and positive cultures. Type III wounds occur months to years post-operatively and are distinguished by draining sinus tracts and chronic osteomyelitis. Type II and III wounds are commonly referred for reconstruction by a plastic surgeon.

We performed a 5-year retrospective review of consecutive patients at Washington DC Veterans Affairs Medical Center evaluating preoperative and post-operative symptoms, pain scores, procedures, length of hospital stay, operating time, outcomes, and complications. Demographics included an average age of 68 years, body mass index 37, and mean albumin 2.9. Risk factors for poor outcome defined as prolonged hospital course or significant postoperative morbidity included hypertension (85%), smoking (90%), and COPD (60%). Thirty-day perioperative mortality was 7%. The resolution of infection and the restoration of sternal integrity can be reliably achieved for recalcitrant mediastinitis in the multiple comorbid patient. Complications occurred in 80% of patients ranging from superficial wound dehiscence, seroma, to deep infection requiring further debridement. Despite this high complication rate, successful closure was achieved in 93% of patients.

Although rare, congenital defects may present to the reconstructive surgeon as Poland syndrome, pectus excavatum, and pectus carinatum. The incidence of Poland syndrome in the general population is 1 in 30,000.⁵⁴

Figure 7 Rectus abdominis muscle. (From THIEME Atlas of Anatomy, General Anatomy and Musculoskeletal System, © Thieme 2005, Illustration by Karl Wesker.)

Chest wall dysfunction may occur in Poland syndrome as a result of abnormalities of the costal cartilages including up to total absence of the anterolateral ribs. Patients may demonstrate lung herniation, deformity of the chest wall, and absent musculature. Absence of the sternal head of the pectoralis major is pathognomonic and may be accompanied by hypoplasia or aplasia of the nipple and breast, shortened ipsilateral upper extremity, and brachysyndactyly.^{55,56} Pectus excavatum is the most common congenital anomaly of the chest and presents a characteristically depressed sternum or “funnel chest” and cardiopulmonary dysfunction that occurs secondarily to rib cartilage overgrowth. Pectus carinatum also occurs due to overgrowth of the rib cartilages, but instead leads to protrusion of the sternum.

Injury after radiation therapy results in significant scarring and nonfunctional tissue. Necrotic or significantly devitalized tissue may require debridement and reconstruction. Ablation of chest wall sarcomas or pulmonary and mediastinal tumors with wide margins requires adequate structural and soft tissue reconstruction to maintain functional integrity. Prior to chest wall reconstruction, the status of a patient’s pleural cavity, the

Figure 8 External oblique muscle. (From THIEME Atlas of Anatomy, General Anatomy and Musculoskeletal System, © Thieme 2005, Illustration by Karl Wesker.)

requirement for skeletal support, and the extent of the soft tissue defect must be fully defined.

CONCLUSION

Acquired chest wall deformities can result from infection, trauma, congenital anomalies, and cancer. A detailed knowledge of chest wall anatomy is crucial for reconstructions in this difficult patient population. Large, complex chest wall defects can be some of the most challenging problems a reconstructive surgeon must face, but successful outcomes may be reliably achieved by adhering to basic principles of adequate debridement followed by obliteration of thoracic dead space, skeletal stabilization, and adequate soft tissue coverage.

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