Chest wall—reconstruction: yesterday, today and the future

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Abstract: Chest wall reconstruction is crucial not only for an uneventful postoperative period after chest wall resection, but also, for ensuring a lifelong good quality of life for the patient. Complex reconstructions should be carefully planned and, sometimes, plastic surgeons are essential for a successful procedure. Various materials and surgical strategies have been developed, giving us the opportunity to choose the best technique for our patient. Emerging developments are mostly based on the use of new materials and the possibility of 3D custom made prosthesis. Currently, this approach is expensive making it exclusive, but in the short term, probably, it will be open for most thoracic units. Nevertheless, we cannot forget that standard surgical procedures, although not so fancy, have demonstrated to be effective and these techniques are universally available. This paper reviews techniques for chest wall reconstruction of large defects from traditional up to the most recently developed techniques.

Keywords: Chest wall reconstruction; chest wall prosthesis; myocutaneous flap; omentoplasty

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Introduction

The chest wall is a complex area of our body that allows breathing even in extreme situations, such as patients with complex malformations. Breathing is possible due to the integrity of all the chest wall layers and when this is lost, the patient is at risk of respiratory insufficiency, ventilatory dependency or even death.

Although chest wall tumors are rare, 50% to 80% of them are malignant (especially over 40 years of age). Up to 60% of those tumors are primary chest wall tumors (1). Moreover, metastatic lesions and lung cancer or breast cancer that invade the chest wall, all of them deserve a wide chest wall excision for a complete resection. Less frequent situations to consider are infections and post-radiation necrosis. In all these cases, chest wall reconstruction should provide the patient with a new stable chest wall allowing an efficient breathing cycle. Soft tissues and skeleton may be replaced depending on the resection. Multiple materials and strategies have been developed for a successful reconstruction.

In this chapter, we focus on complex chest wall reconstructions (2). Resections below 5 cm or in the very apex of the chest, under the scapula or very close to the vertebrae need no specific reconstruction. However, for any other situation, a precise preoperative reconstructive strategy is needed before proceeding. Some conditions are important when attempting a complex chest wall reconstruction:

(I) No matter the type of reconstruction, having an alternative solution in case of failure of the initial strategy is mandatory.

(II) A multidisciplinary team with plastic surgeons is mandatory.

(III) In general, anterior and antero-lateral defects are more demanding than lateral or posterior defects

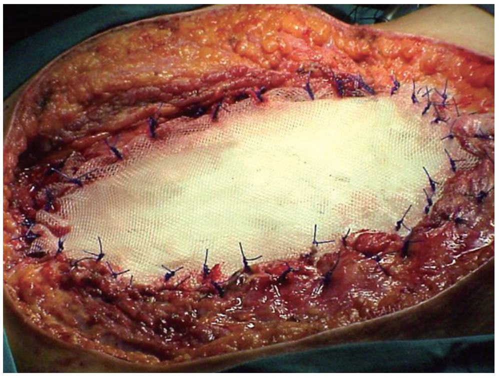

Figure 1 Image of synthetic prosthesis (double layer of polypropylene mesh and sandwich of methylmethacrylate) adapted to cover a wide resection of sternum and ribs.

when planning the reconstruction.

(IV) Always try first autologous tissues instead of prosthetic materials when available.

(V) The scapula can be widely excised before removing the superior extremity leaving, only, some limitations in the shoulder mobility and needing no specific reconstruction.

(VI) If a lung resection has been performed, it is crucial having no air leak at the end of the procedure since it could contaminate the rigid prosthesis hampering the postoperative period.

Skeleton reconstruction

Materials used for chest wall reconstruction/stabilization

The ideal prosthetic material for chest wall reconstruction should have the following characteristics (3):

(I) Rigid enough to abolish paradoxical chest wall motion;

(II) Malleable enough to allow for appropriate contouring;

(III) Physically and chemically inert;

(IV) It should allow for patient tissue in-growth;

(V) Radiolucent;

(VI) Sterile and resistant to infection;

(VII) Not so expensive.

There is not a single ideal material available but a wide variety of synthetic materials such as rigid materials (methyl methacrylate) or flexible as different types of meshes. Generally, we use a combination of these materials, with or without myocutaneous flaps, when complex composite reconstructions are to be performed. Often, the empirical choice of materials depends on the experience of the surgeon and on the local availability of materials due to the lack of definitive evidence (4).

Synthetic mesh: methylmethacrylate, polyglactin, nylon, polytetrafluoroethylene, silastic, silicone, etc.

The most important advantage of flexible meshes is that they are easily manipulated and can be tightened creating the necessary rigidity of the chest wall. Thus, avoiding the paradoxical movement. These materials can be stretched uniformly in all directions, allowing uniform tension strength at the bone defect edges. They are simple to use and usually well tolerated when completely covered by viable tissue. Moreover, these materials provide a barrier that prevents fluid and air moving between pleural and subcutaneous space and form a scaffold for the in-growth of regenerative connective tissue colonizing their outer and inner surfaces. Most of them are porous, thus preventing the formation of seroma.

Traditional techniques

For many years, our preferred choice when reconstructing very large defects of the anterior chest wall, including several ribs and sternum where a rigid patch was necessary, was the use of the sandwich prosthesis with 2 layers of polypropylene mesh and methyl methacrylate. This prosthesis was customized for the chest wall defect of each individual patient during the surgical procedure (*Figure 1*). Despite its advantages, methylmethacrylate material is not permeable to liquids and, can produce pain because of an excessive stiffness of the chest wall. Fractures of methacrylate and an increased risk of infection have also been described. Wound complications are reported in 10% to 20% of patients at 90 days, which requires extraction of the prosthesis in approximately 5% of patients (5).

When it is not necessary to maintain the curvature or the chest wall strength, we prefer the use of a flexible not resorbable patch such as synthetic polytetrafluoroethylene (PTFE) (*Figure 2*). It allows a tight seal and is an excellent scaffold for a myocutaneous flap when necessary (*Figure 3*). The biggest drawback of this patch appears in case of infection, because in this case, it is essential to remove the prosthetic material which will become colonized. Sometimes this can be a difficult procedure (6). Its use is absolutely contraindicated in infected fields.

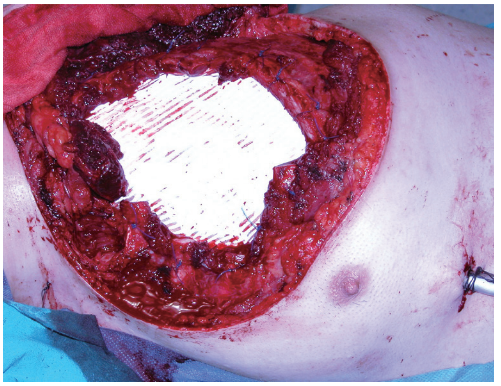

Figure 2 Intraoperative view of a left upper arm disarticulation plus a wide chest wall resection reconstructed with a nonabsorbable synthetic PTFE patch.

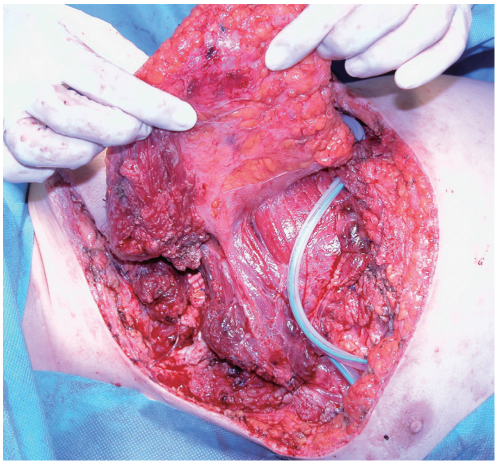

Figure 3 Intraoperative view of the reconstruction of the thoracic wall with myocutaneous flap covering the PTFE prosthesis.

Modern techniques

Osteosynthesis

Osteosynthesis systems are generally based on metallic materials and are used for bridging multiple rib and/or sternal defects. They usually allow for more physiological rib movement than methylmethacrylate or other mesh prostheses. However, they normally need to be used in combination with myocutaneous flaps and/or with meshes to cover complex chest wall defects and isolating the pleural space (7).

Although several rigid metals such as stainless steel and ceramic have been used for chest wall rigid fixation, titanium-based systems have clear advantages over other systems: biocompatibility, osseointegration, resistance to infection, a high strength/weight ratio and low optical density.

The two most common osteosynthesis systems are the titanium-based Stratos® (Strasbourg Thorax Osteosyntheses System), Stracos® (Strasbourg Costal Osteosyntheses System) (MedXpert GmbH, Heitersheim, Germany), Sternalock® (Walter Lorenz Surgical Inc., Jacksonville, FL, USA) and the MatrixRIB Fixation® (DePuy Synthes, West Chester, Pennsylvania, USA) systems. The implantation technique of the Stracos® system entails crimping titanium clips onto the rib to fix simple fractures, whereas Stratos system involves the same crimping titanium clips followed by a bridging titanium bar to fix multi-fractured ribs or bone loss. The Sternalock® and MatrixRIB® systems are based on plates and screws which are screwed directly into the bony edges on both sides of the defect or placed intramedullary in the case of MatrixRIB®.

However, these systems have also some disadvantages. A retrospective study (8) reported a failure of the titanium implant in 44% of patients due to either broken or displaced implants at one year. This incidence of implant failure is unexpectedly high and alarming. It advocates for early removal of the prosthetic material whenever possible and suggests the need for improvements in design.

Bone grafts

Due to some problems related to foreign material use, such as rejection, excessive rigidity, fracture or infection (9,10), bone grafts have been proposed as an effective, durable and biologically well-tolerated solution for chest wall reconstruction. The main advantage of bone grafts is their capability of integration with host tissues. Either iliac bone allograft from a tissue bank (9), autologous ribs harvested from the opposite operative side (10) or for sternal reconstruction (11-13), donor cryopreserved rib allografts (4) or cadaveric cryopreserved sternal allografts (14) have been used. In all cases, reconstruction was achieved by covering the defect with a mesh and/or myocutaneous flap in combination with the bone graft.

According to Aranda *et al.* (4) cryopreserved ribs are far better for reconstruction than other tissue bank bones (8) because size and shape of ribs are easily adjusted to the defect (even when it is irregular) while the limited measures of other implants such as iliac bone grafts can be insufficient to cover large surfaces. Furthermore, costal grafts produce a smaller restrictive effect on chest wall movement and, therefore, preserves a better pulmonary function. On the other hand, cryopreserved allografts eliminate possible morbidity at the contralateral hemithorax donor site (pain, instability, lung herniation) (10) and have no limitations regarding the amount of available bone, because multiple grafts can be obtained from every single donor. Moreover, costal arches are easily harvested, processed and stored for long periods at a reasonable cost. Regarding sternal replacement with cadaveric allograft it is considered an effective procedure which provides optimal stability of the chest wall, the allograft is biologically well tolerated and allows a perfect integration into the host.

Biologic matrices

Biological meshes are biological collagen matrixes derived from porcine dermis in which cells, cell debris, DNA and RNA have been removed to produce an acellular matrix. This allows the remaining collagen to be cross-linked (depending on the commercial variety) with chemical compounds looking for additional stability and reducing degradation (15,16). The final structure combines the rigidity and durability of non-absorbable synthetic materials, allowing integration and remodelling. On the other hand, this structure decreases the risk of site infection associated to prosthetic material. Azoury *et al.* (17) reported a wound complication rate of 31.8% after synthetic reconstruction and 10% after biologic matrix reconstruction, with no abscess formation in the pure biological reconstruction group of patients. Previously, Schmidt *et al.* (18) showed no complications in 6 patients with chest wall defects (80–252 cm^2 wide) that were reconstructed with biological meshes (Permacol®). Nevertheless, D'Amico *et al.* (19) recently reported wound healing difficulties (haematoma or infection) in 3 of 11 patients treated with another type of biological mesh (Protexa®) leaving open the controversy regarding the best material. To improve outcomes, biological meshes are combined with muscle flaps in greater chest wall defects.

Another synthetic meshes

Proceed® patches and flat polypropylene meshes are other useful synthetic materials. Most of the experience with these materials in the thoracic wall is reported in children, in which this type of material has achieved good results in terms of infection and stability (20). However, most of the knowledge about these materials is related to the abdominal-wall surgery experience (21). Recent results showed a slightly lower rate of complications with polypropylene meshes with no significant differences in terms of recurrences or infection when compared to other types of prosthesis (22). Similar results after chest wall reconstruction can be expected, however specific studies in the chest wall should be recommended before assuring these outcomes.

Soft tissue reconstruction

Soft tissue reconstruction is based on the use of transposed/transplanted muscles and greater omentum with the possibility of transposing a skin paddle along with the muscle or free cutaneous grafts for external closure of the defect.

A successful soft tissue reconstruction relies on the precise knowledge of the vascular pedicle of the different muscles. The anatomical position of the pedicle defines the rotation arch of the muscle and the length of the vascular pedicle of the muscles and omentum limits its capacity to reach certain areas of the chest wall. Precise measurements of the available tissue are mandatory before attempting resection. Currently, after an aggressive mobilization of a muscle or myocutaneous flap, it is recommended keeping the patient intubated and hemodynamically stable during the first 24h after the procedure for improving flap survival. Another important measure for better outcome, is not compressing the main vascular pedicle of the flap during the daily wound care. Wounds should be kept covered and local cure should be carried out every two or three days unless signs of complication appear.

Standard rotation and transposition myocutaneous flaps

The muscles more frequently used for chest wall reconstruction are pectoralis major, latissimus dorsi and rectus abdominis muscle. All can be used for microsurgical anastomosis but latissimus dorsi and rectus abdominis are more frequently used than pectoralis major (23-25). The three of them can be mobilized with a local cutaneous graft (myocutaneous flap).

Pectoralis major flap

Pectoralis major muscle is, probably, the first-choice muscle to cover most of the chest wall defects (26). Freeing its inserts to the sternum, ribs, fascia of the rectus abdominis and clavicle as appropriated to the problem, will allow the perfect adaptation of the flap to the defect. Furthermore, it is also possible to release its inserts to the humerus keeping only the vascular pedicle viable and gaining

Figure 4 Post-radiation necrosis at the clavicle level on the left hemithorax after a previous surgery for the same reason but in a lower part of the hemithorax in which a homolateral latissimus dorsi flap was used. An incisional biopsy was performed to rule out a possible secondary neoplasm in her reference hospital. After biopsy (image), a contralateral pectoralis major with a cutaneous island was transposed to close the defect.

Figure 5 Full latissimus dorsi flap.

some extra length for advancing and rotating the flap. This flap is useful in most anterior defects (*Figure 4*) but cannot normally reach the most inferior and central part of the sternum neither the lateral part of the contralateral clavicle, the area of the deltopectoral groove.

Rectus abdominis flap

This flap can provide a large amount of tissue making it useful for large tridimensional defects of the chest wall. However, it can only be used when the superior epigastric artery, its vascular pedicle, is unscathed after resection.

Latissimus dorsi flap

This is the largest muscle of the human body (*Figure 5*); therefore, its flap is wide and versatile. It can be mobilized to cover defects in the lateral and anterior aspects of the chest wall. To use it anteriorly, a complete detachment of the muscle is necessary while keeping the humerus inserction for vascular pedicle protection. The arch of rotation is based on the axillae reaching almost any part of the thorax. The large donor surface produced after its transposition, usually creates a large amount of daily fluid output. Therefore, proper local drainage and compression should be applied, but far from the vascular pedicle area. Patients should anticipate the possibility of long-term drainage duration.

A significant reduction in force and mean fiber area occurs after transposing the muscle despite an intact neural support. Besides, according to experimental results, nearly 70% preservation of maximum isometric tension and higher resistance to fatigue is found in the transplant muscle when compared to the transposed muscle supporting the use of micro-neurovascular muscle transplantation as a better option (27).

Special situations

Microsurgical flaps

The introduction and development of microsurgery expanded the arsenal of reconstructive techniques for complex defects coverage (28) when no local or transposable tissue is available. The most frequent flaps are:

(I) Tensor fascia lata musculocutaneous flap. This flap has two main advantages: the presence of a large vascular pedicle that allows performing the anastomosis far from the area of tissular damage; and the possibility of harvesting the flap as a fasciocutaneous or as a myofasciocutaneous flap. The flap is well tolerated with low complications at the donor site (29).

(II) Deep inferior epigastric perforator flap (DIEAP). This flap has also a long vascular pedicle but is especially interesting because of the large volume of tissue that can be mobilized (30).

Flaps based on perforators (31,32)

Internal mammary artery perforator flap (IMAP)

Mammary artery is responsible of irrigating the skin in the anterior part of the thorax through its perforator vessels. It launches perforators in each intercostal space. However, only the first (occasionally), second, third and fourth intercostal spaces perforators are useful for creating a robust flap. Viability of the vessels must be evaluated using Doppler ultrasound before proceeding. It allows

Figure 6 Detail of the superior epigastric perforator flap planned for covering the lack of sternum and central costal cartilages at the inferior part of the anterior chest wall.

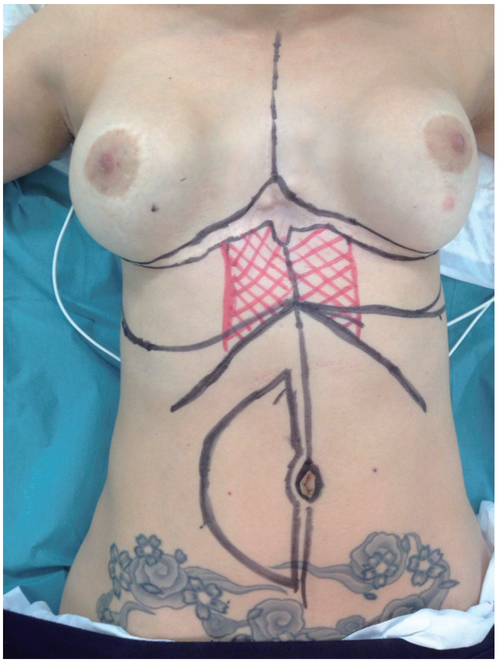

Figure 7 Complete preoperative planification of the case. Two flaps were drawn: superior epigastric perforator flap and rectus abdominis flap.

harvesting a cutaneous paddle from the middle line to as far as the axillae using the skin of the upper third of the anterior chest wall (Bakamjian flap). The cutaneous paddle can be rotated 180 degrees for a perfect fit. It offers a good flap when the pectoralis major flap cannot be used (33,34). The arch of rotation of the flap can be enlarged resecting one or two costal cartilages after careful dissection of the internal mammary artery.

Superior epigastric artery perforator flap (SEAP) (35)
The superior epigastric artery is the terminal branch of the mammary artery. Under the seventh costal cartilage, it branches toward the surface delivering the first perforator or superior superficial epigastric artery. This disposition allows creating a flap useful to cover the inferior third of the sternal area (*Figure 6*), an area the pectoralis muscle and latissimus dorsi cannot reach most of the times. This advancement flap avoids the morbidity associated with the transposition of the rectus abdominis flap (*Figure 7*).

Omentoplasty (36)

The greater omentum is a very active tissue in wound healing. A good vascularization pattern and the immunological properties of the greater omentum flap build the basis of its capacity of cellular proliferation and repairment function (37). Probably is the best tissue when approaching a very large defect (2). It creates a good basis for a free skin graft. The omentum can be prepared by open laparotomy or laparoscopy and must be tunneled toward the surface to reach the area of coverage. It can be also transplanted using microsurgery (38).

Future technique

After the release of our former 3D custom-made prosthesis (39), we realized the need for further improvements that we have already included in the second generation of custom-made prostheses that we have implanted (data not been yet published awaiting for middle and long-term outcomes assessment).

There are plenty of exciting ongoing developments for a more personalized approach to chest wall reconstruction. However, to ensure that all efforts are directed in the same direction any new technique should adhere to the Okereke's postulates (40) which are: clear indications, contained costs and demonstrable functional results to improve the limited actual prosthetic designs (41-43). New research using mathematical models that consider the rib cage as a whole (44) along with the development of new generation materials with an improved mechanical behaviour (45) are intended to improve osseointegration (46) and bone adaptation to the prosthesis (47). All this opens the possibility of designing customized prostheses depending on the area of placement and the state of the recipient bone. Moreover, this is especially interesting in the case of pediatric patients where adaption of chest wall reconstruction to the child's growth and development is crucial (48,49).

Besides this, future chest wall implants will not be mere inert structures but will have therapeutic capacity. Recent studies have proved feasible the development of stimuli-responsive nanosystems based on mesoporous silica nanoparticles as ultrasound-responsive drug carriers (50) or the adaptive-response bioceramics for antimicrobial purposes (51).

The final stage of this journey into the future of chest wall reconstruction is tissue bioprinting. Although functional solid organs are beyond the capabilities of current biofabrication technologies, the preliminary steps towards this goal are being taken in the form of new porous biomaterials that mimic the topological, mechanical, and mass transport properties of bone (52). An even more specific approach would be the use of tridimensionally-printed biological scaffolds that would be colonized by cells from the patient once implanted, such as those made of alginate plus polycaprolactone that mimic the geometry of a vertebral body and are capable to support the marrow structure (53). Another possibility is the use of two-phase systems consisting of differentiation and growth factor-loaded nanoparticles embedded into printed biocompatible scaffolds with porous microstructures seeded with stem cells (54,55), since some of them offer promising results even in cases of full-thickness chest wall defects (56).

In this race towards the bioprinting of functional complete organs, the reports of the Wake Forest University group have been a real milestone. In 2015, they reported a new printing system with cell-laden hydrogels together and synthetic biodegradable polymers that overcome many of current limitations for structural integrity and mechanical stability of three dimensional bioprinted constructs (57). More recently they have developed *in vitro* organized bioprinted muscle tissue constructs with neuromuscular junction robust enough to maintain structural and functional characteristics *in vivo* (58). In this same line, the Spanish group of Cubo *et al.* (59) have successfully printed a human bilayer skin using bio-inks containing human plasma as well as primary human fibroblasts and keratinocytes obtained from skin biopsies.

What's next in chest wall reconstruction? Given the current level and speed of development, this is a really difficult question. Maybe nothing is impossible, and the myth of self-regeneration is closer becoming a reality, as suggested by Kurita *et al.* (60) with their impressive research on generation of expandable epithelial tissues using *in vivo* reprogramming of wound-resident mesenchymal cells.

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Footnote

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at http://dx.doi.org/10.21037/shc.2019.02.02). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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