Review Article

Sternal resection and reconstruction: a review

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Abstract: Sternal resection and reconstruction is a rare but sometimes challenging procedure due to its profound anatomical and functional implications. For these reasons, an adequate preoperative evaluation is crucial in each patient, especially when we are faced with malignant lesions that sometimes require extensive radical resections, thus demanding an integrated reconstructive strategy that allows stabilizing the chest wall, protecting the underlying mediastinum and minimize resulting deformity. The large number of available reconstruction techniques and the lack of quality studies for their analysis mean that sternal reconstruction depends to a great extent on the consensus of experts or, more frequently, on the simple preference of each surgical team. This article aims to provide an overview of sternal resection and reconstruction. Indications for partial versus total or subtotal sternectomy are suggested and their surgical and oncological outcomes are presented. The use of rigid or semi-rigid prostheses is an ongoing debate, although recent functional data advise reserving rigid reconstructions for extensive defects. Sternectomy for primary tumors or local tumor involvement has a good prognosis with an overall survival of 5 and 10 years: 67% and 58%, respectively, provided that a radical resection with free surgical margins is performed. Breast cancer is the most common secondary sternal tumor, and surgery can offer 5-year overall survival ranging from 20% to 50% provided an R0 resection is achieved, although radical surgery does not appear to decrease rates. of recurrence. Metastases of origin other than the breast give the worst results (less than 40% at 36 months and 0% at 5 years) and although the data available on these cases are limited, the radicality of the resection does not seem to modify the survival or recurrence rates, so a conservative approach is probably more appropriate.

Keywords: Sternum; resection; reconstruction

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Introduction

Sternal resection and reconstruction is not a common chest wall procedure, but when one of these cases occurs, its management can be challenging. Even after small partial resections of the sternum, both thoracic cavities are at risk of instability, so it is crucial to ensure not only aesthetic but mainly protective and functional restoration to preserve respiratory mechanics. Therefore, any sternal resection must begin with a careful patient selection including evaluation of operability and resectability followed by selection of the most appropriate technique for reconstruction. Unfortunately, a large variety of options are available and the existing data for their evaluation come mainly from retrospective single center studies including few patients. Since randomized trials and even comparative studies between different techniques are lacking, the available knowledge on sternal reconstruction depends largely on expert consensus or more frequently on the simple preference of each surgical team.

In this sea of uncertainty, the objective of this article is to offer an overview of the preoperative evaluation,

Table 1 Indications for sternal resection

Primary malignant tumors	
Chondrosarcoma	
Osteosarcoma	
Others	
Secondary malignant tumors	
Local involvement	
Lung carcinoma	
Mediastinal neoplasms	
Metastatic carcinoma	
Breast cancer	
Plasmacytoma	
Melanoma	
Others	
Benign tumors	
Chondroma	
Bone cysts	
Others	
Non-tumoral lesions	
Sternoclavicular joint infection	
Radiation injuries	

Sternal resection indications (in descending order of frequency).

indications, techniques and results of sternal resection and reconstruction, trying to describe the main advantages and disadvantages of each type of technique in order to facilitate the most appropriate choice in each specific clinical case.

Indications for sternal resection (*Table 1*)

Sternoclavicular joint infection

The sternoclavicular joint includes the clavicular notch of the manubrium, the sternal head of the clavicle, and the costocartilage of the first rib. In certain circumstances such as intravenous drug use, local trauma and some immune compromised states such as diabetes, chronic hemodialysis or longstanding steroid therapy, this joint can get infected and failure to control infection by conservative means might mandate surgical resection (1,2).

Radiation injuries

Months or even years after radiation therapy, some patients experience a serious local complications known as late radiation tissue injury (1). Due to obliteration of tissue small vessels, a progressive deterioration secondary to reduced vascularity occurs, followed by replacement of normal soft tissue architecture by dense fibrosis that ultimately leads to tissue ulceration. In such cases, wide surgical resection plus coverage with a well vascularized soft tissue flap might be the only chance to avoid progressive necrosis and infection.

Neoplasms

Primary sternal tumors are rarely benign, consisting of chondroma, bone cyst, fibrous dysplasia hemangioma, osteoma or Langerhans cells histiocytosis (3,4). Much more often they are malignant, most of them being chondrosarcomas and osteosarcomas. While osteosarcomas may be treated with neoadjuvant chemotherapy, chondrosarcomas are unresponsive to radiation or chemotherapy, therefore complete surgical resection is their only chance for cure. Other infrequent primary tumors such as squamous cell carcinoma have also been described (5).

Secondary sternal tumors are uncommon, representing about 15% of all sternal tumors and involving mainly the body of the sternum (6). Among these lesions we find both sternal invasion from adjacent diseases such as breast or mediastinal tumors (thymic carcinoma, germ cell tumors and others) as well as purely metastatic lesions. Among the latter, breast cancer is usually the most frequent with up to 50% incidence in some series (7) but other possible metastatic tumors are solitary plasmacytoma (8), renal cell cancer (9), melanoma (10), thyroid carcinoma (11), colorectal cancer, cervical cancer, hemangioma (12) or hepatocellular carcinoma (13). Given their overall low incidence and therefore limited published data, there is no consensus on their treatment (13), though given their bad prognosis and the high rate of incomplete resections performed the trend is towards limited palliative exeresis to avoid pain, infection or pulmonary function impairment, always within a multimodal treatment scheme (7).

Preoperative assessment

As in other thoracic procedures, preoperative diagnostic encompasses the evaluation of operability and resectability, as well as a detailed reconstruction plan. All of them should ideally carried out by multidisciplinary teams including at least thoracic surgeons, plastic surgeons, anaesthesiologists and physiotherapists.

Operability workup

The operability assessment for sternal resection does not differ much from that required for any other major thoracic intervention and must include a thorough clinical history plus physical examination, some laboratory tests and a final cardiopulmonary evaluation. Within the clinical history, the underlying respiratory diseases (especially if they are oxygen-dependent) are relevant, since even a small surgery can produce a high postoperative dysfunction (14). Other important parameters to be recorded are evaluation of daily life activities, nutritional status, sarcopenia (progressive and generalized loss of skeletal muscle and strength) or frailty (unintentional weight loss, fatigue, poor grip strength, inactivity and low walking speed), a variable related to postoperative adverse outcomes (15,16).

After clinical history, a complete physical examination is mandatory, being important again to search for signs and symptoms that may indicate frailty. Operability evaluation is finally completed with the usual laboratory tests and a structured cardiopulmonary assessment according to current guidelines (17).

All this information allows us to classify our patients as low, medium or high risk patients, these latter being those with a score equal or higher than 4 in a frailty scale, severe comorbidity and/or high cardiac and/or pulmonary impairment; in such cases, a possible solution is proceed with a surgical prehabilitation or preoperative intervention on those adverse conditions that can worsen postoperative results (18-22).

Resectability workup

The assessment of resectability differs between benign and malignant lesions. In the first case, it is usually based on less invasive techniques such as the isolation of pathogen cultures in the case of infections and is mainly aimed at distinguishing between the need for medical or surgical treatment.

In the case of a tumor, the evaluation is aimed at evaluating the type of resection necessary, the required surgical margin and, where appropriate, the best reconstruction technique. It should include both a diagnosis by biopsy of the type of tumor and its degree of differentiation as well as a staging as accurate as possible.

Staging is usually performed by image methods such as plain radiograph, axial computed tomography (CT) scan, magnetic resonance image (MRI) or positron emission tomography-CT (PET-CT). CT scan is the most sensitive and commonly used tool but may not be reliable when assessing depth of invasion (23-25), therefore other techniques such as ultrasound (26,27), dynamic CT scan, two-step CT scan (28), MRI (29) or cine MRI (30) have been proposed to increase accuracy with mixed results. PET-CT is considered clearly suboptimal to assess sternal invasion due to blooming artifact, which may overestimate the size of the lesion (31). Finally, to get information about the type of tumor and its differentiation, available resources are fine needle aspiration, core needle biopsy and incisional or excisional biopsies according to the case (32,33).

Strategies for resection

Sternoclavicular joint infection

Surgery is usually performed via an inverted L-shaped incision that extends laterally over the medial half of the clavicle and inferiorly over the manubrium down to the second or third interspace (1). Devitalized soft tissue is widely debrided and if the damage is judged not important, vacuum assisted closure (VAC) dressing can be attempted for closure by secondary intention. When tissue destruction is extensive, half the manubrium is typically resected to preserve stability of the contralateral side and the costal cartilage and medial portion of the first rib can then be divided with rib instruments, along with medial portions of the second or third rib if involved with infection. In such cases, soft tissue coverage for closure is required, most commonly with an ipsilateral pectoralis muscle flap (2). The use of a prosthetic reconstruction is contraindicated due to infection risk, thus biological meshes are preferred.

Radiation injuries

Once underlying malignancy has been ruled out, the general management of these lesions includes debridement of necrotic tissues and reconstruction with well-vascularized flaps (1). Mesh reconstruction should be avoided due to the risk of infection and is generally unnecessary as due to the chronic nature of infection there is always some degree of

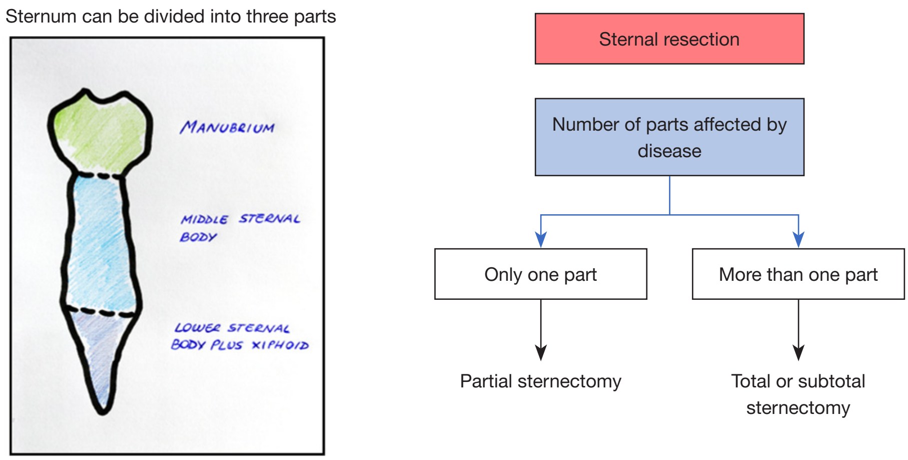

Figure 1 Proposed treatment algorithm for sternal resection.

fibrosis that stabilizes by itself the chest wall (2).

Neoplasms

Resection of the sternum often requires extensive excision of the overlying skin and soft tissues along with the affected part of the bone, sometimes extending to the adjacent pericardium, thymus, large blood vessels, and other major organs (3). Since complete resection with free surgical margins is crucial for the prognosis of these tumors, radicality is usually the norm, as demonstrated by a recent consensus study where up to 41% of surgeons agreed that the skin of the tumor surface should be extensively excised even though imaging and palpation examinations did not indicate invasion (34), thus surgical access is usually made through a vertical, elliptical incision that encompasses not only the tumor but all the affected surrounding structures.

In tumors that involve more than one part of the bone (considering a division of the sternum into manubrium plus medial third of the clavicles, middle sternal body and lower third of the sternal body plus xiphoid) (*Figure 1*), a subtotal or total sternectomy is performed. Partial sternectomies are reserved for more localized tumors (4). Some authors (35) have even reported more conservative approaches with preservation of the posterior cortex of the sternum, but in our opinion, since an R0 resection is necessary to avoid the high risk of tumor recurrence and since these supposedly limited resections frequently include skin, soft tissue or ribs excision, its advantages are highly questionable.

Regardless of the type of resection, most authors agree that a minimum margin of 3 cm is considered necessary to minimize the risk of local recurrence (34). As these resections are often extensive, they require planning for both skeletal and soft tissue reconstruction and, in cases where reconstructive surgery cannot be performed due to close vicinity of the tumor to vital organs, a positive surgical margin (R1) is allowed, always considering postoperative radiotherapy. As a particular situation, in manubrium sterni tumors, a large percentage of surgeons believe that the capsula articularis sternoclavicularis can be used as a safe margin marker if the tumor does not invade the joint capsule (34).

Reconstruction techniques

The goals of sternal reconstruction are to stabilize the chest wall to minimize the risk of prolonged mechanical ventilation and respiratory complications, to protect the underlying mediastinum, and to minimize the resulting deformity. Sternectomies defects often involve resection of the overlying skin or sacrifice of the internal mammary vessels, and furthermore patients undergoing oncologic resections typically present with an impaired wound healing secondary to adjuvant chemoradiation. Thus, oncologic sternectomy creates heterogeneous clinical scenarios that demand an integrated reconstructive strategy (3,36).

The review of the literature on prosthetic reconstruction is hampered by several limitations, the strongest of which is the absence of prospective trials comparing different techniques and materials with each other because of the low surgical volume, even in specialized centers. Furthermore, most single-institution experiences encompass multiple

Table 2 Advantages and disadvantages of different sternal reconstructive techniques

Type of technique	Advantages	Disadvantages
Non-rigid methods		
Soft tissue (omentum)	Protect from friction against other prosthetic material, well vascularized tissue	Available omentum amount highly variable, difficult harvest if previous abdominal surgery
Meshes	Available, cheap, easy to handle and store	Low resistance to infection, poor protection of vital organs
Synthetic (braided)[†]	Good tissue ingrowth, thinner	
Synthetic (compact)[‡]	Bad tissue ingrowth, impermeable, thicker	
Biological[§]	Rigid, durable, good tissue integration, decreased infection risk	
Rigid methods		
Bone allografts[¶]	No donor site morbidity; unlimited availability; easily adjusted; cost-effective	Possible graft reabsorption
Prosthesis	Immediate stabilization of chest wall (low risk of respiratory complications), acceptable cosmetic results	Little real tissue integration, high risk of migration, fracture or erosion, low resistance to infection
3D printed prosthesis[††]	More precise setting of resection margins, minimal intraoperative adjustment, shorter surgery, less dislocation or migration, reduced pain, improved aesthetics	Indications of use not clearly defined, higher cost, no data about functional outcomes

[†], e.g., polyester or polypropylene meshes; [‡], e.g., PTFE meshes; [§], refers to dermis crosslinked collagen matrixes; [¶], iliac bone, rib or sternal allograft from tissue bank; [††], theoretical advantages of 3D printed prosthesis over other standard devices. PTFE, polytetrafluoroethylene.

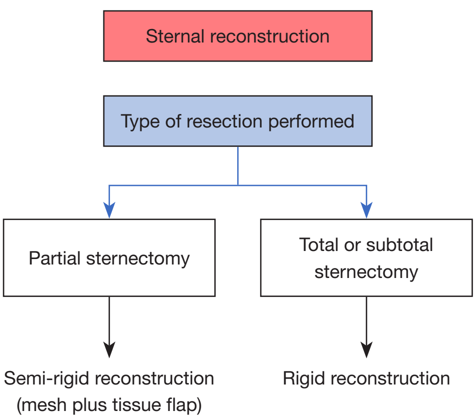

Figure 2 Proposed treatment algorithm for sternal reconstruction.

decades, and therefore do not optimally show the continuous refinements in patient selection, surgical technique, reconstructive materials, and postoperative care. To end, some outcomes, such as patient quality of life and cosmetic considerations, have seldom been measured scientifically but are often postulated (37). Consequently, the choice of technique to use often depends on previous surgical experience and surgeon preference rather than on the demonstrable superiority of one technique over another for that particular defect (*Table 2*).

Although the extent of resection that mandates a rigid versus semi-rigid reconstruction (this latter being those composed solely of meshes and soft tissue flaps) remains to be determined, in a recent publication, the majority of patients (85%) undergoing a total or subtotal sternectomy received some rigid prosthetic reconstruction (36), which together with some encouraging results with semi-rigid reconstructions for partial sternectomy defects point to a shift to reserve rigid reconstructions for more extensive sternectomy defects (*Figure 2*).

Sometimes, some specific situations may demand even more specific technical solutions. The sternoclavicular joint disruption represents a particular technical defy, because the shoulder and upper limb are destabilized, leading to pain and dysfunction as the shoulder internally rotates and medially displaces (38), but authors such as Rocco *et al.* (10) found a full range of mobilization of the shoulder without reconstruction of the clavicles more than three months after surgery. Sometimes the effort to preserve the upper

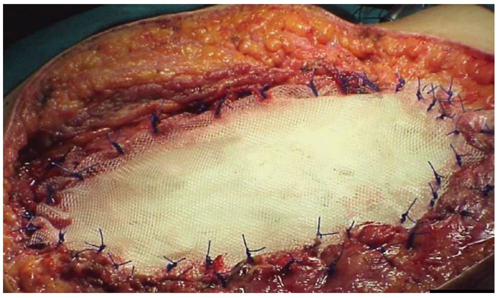

Figure 3 Methylmethacrylate plate sutured to rib stumps after an extensive sternocostal resection.

portion of the sternum to minimize a possible functional alteration carries a high risk of recurrence due to positive surgical margins, so when in doubt a complete resection for oncological benefits is strongly advised (39). Another particular case for reconstruction is children, where complications related to prosthetic materials and their probable growth restriction make bone grafts and biological meshes specially preferred although again no studies reporting mid-long term results are available (12).

Non-rigid reconstructive methods

Soft tissue coverage

Since sternal defects may require complex soft tissue reconstruction, which is usually performed by an experienced plastic surgeon, a description of the many soft tissue coverage options is well beyond the scope of this article. Generally, pectoralis major muscle advancement flaps without disinsertion are the preferred reconstructive option and if these are not present or diminutive, a distant free flap is selected such as a fasciocutaneous flap from the leg, abdomen, or the thorax. Omental flaps are also a reliable option for sternal reconstruction (38,40,41) as they protect mediastinal organs from friction against any other added prosthetic material and provide a well vascularized tissue with a rich lymphatic network (42).

Meshes

There is a great variety of flexible implants (generically known as "meshes") classified according to their composition (synthetic or biological) or their properties (knitted of compact, etc.). Well-known advantages of meshes are their availability, cheapness and easiness to be handled and stored but as opposed they are poorly resistant to infections and sometimes do not provide enough protection for vital organs. Despite a formal comparison between different types of meshes has not been performed and their postoperative outcomes are similar to those of autologous flaps (43), meshes seem to be one of the most preferred techniques of reconstruction, as they were used by an 82.5% of surgeons in a recent consensus study (34). The quality of life and patient satisfaction after their implantation is clearly improvable, as stated in the study by Daigeler *et al.* (44) where only 38% of patients described it as much or slightly better.

Synthetic meshes

Several studies conclude than sternal reconstruction with a synthetic mesh provides a secure base for reconstruction but needs to be covered by a muscle flap (what is called a semi-rigid reconstruction) to avoid paradoxical respiration (45,46).

Braided or reticular meshes (polyester, polypropylene, etc.) are permeable to air and liquid, allowing connective tissue cell ingrowth; not being very thick, some are used for rigid reconstruction in combination with other materials such as methyl methacrylate (*Figure 3*). Compact meshes such as polytetrafluoroethylene (PTFE) are thicker and more impermeable to air and liquid, but favour tissue growth to a lesser degree. As an intermediate solution between flexible and rigid implants, the use of titanium meshes has been proposed. These devices seem easy to cut and shape, achieving the right rigidity on the chest wall while preserving the elasticity and dynamics of the thorax, resulting well tolerated by the patient (47-49).

Biological meshes

Biological meshes are usually biological crosslinked collagen matrixes derived from porcine dermis in which cells, debris and all genetic material have been removed (50). The final structure combines the rigidity and durability of non-absorbable synthetic materials with the ability for tissue integration and remodelling, which would make it especially interesting in cases of pediatric reconstructions given the possibility of growing with the patient. Due to its capacity for tissue integration, this material is also advocate to decrease the risk of site infection associated to prostheses although there is still an open debate since some authors (51) reported the occurrence of wound healing difficulties (haematoma or infection) in several patients while other recent studies with follow-up periods of about two years report no postoperative complications with good functional outcomes (52,53).

Rigid reconstructive methods

Allografts

Either iliac bone allograft from a tissue bank (54-57), donor cryopreserved rib allografts (58) or cadaveric cryopreserved sternal allografts (59,60) have been proposed as a simple and cost-effective technique for sternal reconstruction.

Autologous iliac graft was one of the first bones to be used for sternal reconstruction in combination with titanium bars. A common drawback for this implant is it limited size, which makes it unsuitable to cover large surfaces. Moreover, the combination of the graft with the fixation bars results in fact in a "rigid plate-effect" with consequences very similar to those of methylmethacrylate sandwiches. In this sense, the largest published series (56) registered up to 66% of postoperative complications, most of them cardiopulmonary.

In our own experience (58), cryopreserved ribs are far better for reconstruction than other tissue bank bones because size and shape of ribs are easily adjusted to the defect, even when it is irregular. Its use seems especially interesting for sternal manubrium reconstruction as stated by Zhang *et al.* (61). These grafts eliminate possible morbidity at the contralateral hemithorax donor site (pain, instability, lung herniation) and have no limitations regarding the amount of available bone, processed and stored for long periods at a reasonable cost.

Sternal replacement with cadaveric allograft is also considered an effective procedure which provides optimal stability (59). The largest series published is a multicenter study encompassing 58 patients submitted for sternal resection due to primary and secondary tumors and other non-neoplastic conditions; median postoperative follow-up was of 52 months with a 30-day mortality of 5% and a morbidity rate of 31%, mostly secondary to respiratory complications or surgical wound problems. Interestingly, no respiratory deficiency or complications derived from insufficient or altered ventilatory mechanics were recorded and the graft integrated perfectly into the host as recently demonstrated by bone scintigraphy scans (60). As a particular modification of this technique, Rosenberg *et al.* published the complete resection of the sternum with *ex vivo* curettage, cryotherapy and posterior reimplantation in a case of breast carcinoma metastasis (62).

Finally, some other strategies have been explored such as fascia lata grafts (63), free vascularized iliac osteocutaneous flaps (64) or even regenerative approaches with strategies aimed at promoting tissue regeneration with bone remodelling using cell therapy based on mesenchymal stem cells (6).

Prostheses

The term "prosthesis" encompasses a wide variety of devices that range from the relatively simple systems such as methylmethacrylate sandwiches to the more complex titanium devices. Most of them allow an immediate stabilization of the chest wall with a possibly lowered risk of respiratory complications and good cosmetic results but at the same time tend to have little tissue integration and a high risk of migration, fracture and erosion as well as low resistance to infection. However, whether these complications primarily relate to the kind of prosthesis or to confounders, such as the size of the chest wall defects or the type of soft tissue transposition for coverage, is impossible to determine within the context of the available retrospective studies (37).

One of the first synthetic rigid implants were methylmethacrylate plates, also known as "sandwich meshes" (*Figure 2*). In our opinion, this type of reconstruction is slightly outdated by many other techniques as it can produce ventilatory restriction, has an increased risk of migration and erosion and causes discomfort to the patient (if not directly pain) because of an excessive stiffness of the chest wall. Wound complications such as seroma or infection are reported in 10% to 20% of patients at 90 days, which requires removal extraction of the prosthesis in approximately 5% of cases (65).

From these first prostheses many other different techniques have been proposed for rigid chest wall reconstruction with variable results such as the use of other mesh-bone cement sandwiches (66), Kirschner wires (67), steel sutures (68), ceratite prosthesis (69), porous alumina (70), Ley prosthesis (71), rib-like technique (72) or customized sternal plates (73,74) but titanium-based devices are by far the most commonly used nowadays. They have clear advantages over other systems (biocompatibility, osseointegration, resistance to infection, a high strength/weight ratio and low optical density), although they are not free of complications similar to other devices such as rupture, displacement, thoracic pain or infection (47,50). Common osteosynthesis systems are Stratos® (Strasbourg Thorax Osteosyntheses System), Sternalock® (Walter Lorenz Surgical Inc., Jacksonville, FL, USA) or the MatrixRIB

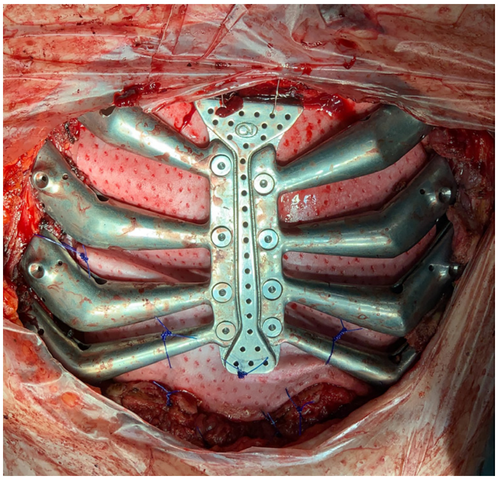

Figure 4 Modular 3D printed prosthesis with a common central axis plus modifiable "lateral combs" according to the type of reconstruction required.

Fixation® (DePuy Synthes, West Chester, PA, USA) while some other companies also offer made to measure titanium implants. Although widely available and highly customizable in different surgical settings, 3D printed prostheses could be the next generation of these devices.

3D printed prostheses

Additive manufacturing (also known as 3D printing) is a technology that allows to manufacture all sort of pre-designed objects by depositing layer upon layer of different materials such as plastic, metal, ceramics and others (75). Versus other types of rigid implants, 3D printed prosthesis offers some theoretical advantages such as a more precise setting of resection margins, minimal need for intraoperative adjustment and better fixation systems to prevent dislocation or migration. As a consequence, the operative time is shortened, pain is reduced and aesthetics are improved (76).

Many different materials have been proposed as the ideal for sternal 3D printed prostheses yet titanium being still the most widely used (34,77). However, from a functional point of view, new bone-like materials such as polyether-ether-ketone (PEEK) has an elastic modulus closer to that of cortical bone and are promising alternatives to titanium as it improves integration into the host with less functional impairment (78).

Despite all the possible advantages, these devices are far away of being considered as a day-to-day technology in our specialty. Against a large number of experimental studies, there are few clinical studies, mostly heterogeneous and limited to clinical cases without information about mid- and long-term outcomes, thus making impossible to address fundamental questions such as the precise use indications of these devices, their real outcomes compared to other well-known reconstructive techniques or even their supposed unaffordable cost (79). There is a clear need for collaborative studies in order to standardize this device as much as possible, this meaning to agree on some general designs and materials for the sternal prostheses, so that only a few minor adjustments in each particular case are made. This would allow mass-production which would reduce costs, manufacturing time and simplify some regulatory hurdles. Our group is precisely in this line of work through the development of modular sternal 3D printed prostheses with a common central axis and modifiable "lateral combs" according to the needs of each patient (80) (*Figure 4*).

Resection and reconstruction outcomes (*Table 3*)

Mortality, morbidity and functional outcomes

Despite his apparent aggressiveness, sternal resection seems to be a safe surgery. Overall complication rates for reconstructions of partial and total or subtotal sternectomies were equivalent which could justify the trend towards more aggressive resections (36).

Mortality rates ranged from zero to 7% in most published series (81-84). Deaths were usually secondary to systemic respiratory complications that with an incidence of 1.1% to 24.4% are the main source of morbidity after chest wall resections due to flail chest and paradoxical breathing resulting in sputum retention, atelectasis, pneumonia and respiratory failure (36,42,81-85).

Local morbidity was commonly related to wound complications (pain, seroma, infection, dehiscence) or device-related problems such as prosthesis erosion, fracture, displacement or migration (3).

After sternal resection and reconstruction, many authors have focused on the in-hospital period only, while in other studies the data mainly refer to survival, recurrence, and metastasis rates. Only sporadic reports focusing on quality of life and postoperative pulmonary function exist.

Because of immediate stabilization, the use of prostheses is especially attractive for sternal reconstruction, although this topic remains subject to controversy. On the one hand, several works support the idea of that the repercussion on respiratory mechanics of sternal resection may not be

Table 3 Series on sternal resection and reconstruction

Author	Patients	Indications†	Resection†	R0 percentage	Reconstruction‡	Complications§
Dudek *et al.* (7)	8	SM	TS [2], PS [6]	50%	Methylmethacrylate, synthetic meshes, titanium plates	Empyema, hemothorax, subclavian vein thrombosis
Butterworth *et al.* (36)	49	PM [12], SM [31], OT [6]	TS [13], PS [36]	Non stated	Rigid reconstruction [18], semi-rigid reconstruction [22], no reconstruction [9]	Prolonged mechanical ventilation, pulmonary embolus, wound complications, mesh removal, in-hospital mortality [1]
Fabre *et al.* (39)	24	PM [9], SM [15]	TS [24]	Non stated	Titanium-rib bridge	Pulmonary infection, seroma
Gritsiuta *et al.* (42)	4	PM [4]	TS [3], PS [1]	Non stated	Methylmethacrylate, prolene mesh, titanium plates, biological mesh	"Complicated hospital course" [1]
Gonfiotti *et al.* (52)	27	PM [18], SM [9]	TS [5], PS [22]	Non stated	Biological mesh	None
Xu *et al.* (56)	12	PM [3], SM [4], BT [2], OT [3]	TS [10], PS [2]	Non stated	Iliac graft + titanium plates	Pleural effusion, pulmonary infection, atelectasis, atrial fibrillation, tissue flap necrosis [8]
Marulli *et al.* (59)	14	PM [8], SM [5], OT [1]	TS [2], PS [12]	Non stated	Sternal allograft	Displaced implant, wound dehiscence
Dell'Amore *et al.* (60)	58	PM [15], SM [13], OT [30]	TS [42], PS [16]	Non stated	Sternal allograft	Respiratory complications, wound complications [18], in-hospital mortality [3]
Zhang *et al.* (61)	12	PM [5], SM [3], OT [4]	TS [7], PS [5]	Non stated	Rib allografts	Paradoxical movement of the chest wall
Puviani *et al.* (63)	8	PM and SM	TS [8]	Non stated	Fascia lata graft	Wound complications
Girotti *et al.* (72)	101	PM [42], SM [52], OT [7]	TS [24], PS [77]	93%	Synthetic mesh, rigid prosthesis, rib-like technique	Cardiorespiratory complications [7], wound infections, graft necrosis [15], prosthetic removal [7]
Marulli *et al.* (81)	23	PM [23]	TS [18], PS [5]	85,4%	Rigid reconstruction, semi-rigid reconstruction	Cardiorespiratory complications [5], wound complications [2], others [4]
Bongiolatti *et al.* (82)	36	PM [23], SM [13]	TS [6], PS [30]	100%	Rigid reconstruction, semi-rigid reconstruction	Cardiorespiratory complications [7]
Ahmad *et al.* (83)	78	PM [28], SM [45], OT [5]	TS [73], PS [5]	77% TS, 72% PS	Synthetic mesh, biological mesh	Cardiorespiratory complications [17]
Novoa *et al.* (84)	6	SM [6]	TS [2], PS [4]	Non stated	Methylmethacrylate, PTFE mesh	Respiratory insufficiency with mechanical ventilation [1]
Elahi *et al.* (85)	93	PM [45], SM [48]	Non stated	69%	Methylmethacrylate, synthetic mesh, osteosynthesis	Cardiorespiratory complications [36], wound complications [7], other [5]
Leuzzi *et al.* (86)	35	PM and SM	Non stated	71%	Synthetic mesh, no reconstruction	Anemia, seroma, atelectasis, respiratory failure

†, number for each subset in square brackets. ‡, all the reconstructions added a soft-tissue flap coverage. Number of cases in square brackets. §, number of patients for subsets in square brackets. SM, secondary malignant tumors; TS, total/subtotal sternectomy; PS, partial sternectomy; PM, primary malignant tumors; OT, other non-neoplastic diseases (radionecrosis, sternoclavicular joint infection); BT, benign tumors; PTFE, polytetrafluoroethylene.

as severe as previously thought (86); thus, when part of the distal sternal third or a small part of the manubrium with the sternoclavicular joint is preserved, rigid materials might not be essential and primary closure or a semi-rigid reconstruction could be enough as no differences were observed between the pre and postoperative respiratory function (87-90). On the other hand, authors like Scarnecchia (91) systematically recommend rigid reconstruction in the so-called critical areas of the chest such as the anterior chest wall because its stabilization showed an inverse correlation with acute respiratory complications, flail chest and deformities (100% occurrence in the non-reconstructed subgroup versus only 5.7% after reconstruction). Moreover, not even the most rigid prostheses such as methylmethacrylate sandwiches seem to pose a high restrictive effect on lung function, since evidence up to 92% concordant movement of the wall and the prosthesis 6 months after surgery, with no relevant differences between preoperative and postoperative lung function (92). Since neither of the two types of prosthesis has a great impact on lung mechanics, it seems reasonable, to reserve rigid reconstructions for more extensive sternectomy defects to reduce the risk of infections, patient discomfort and the cost of the procedure.

Data about *in vivo* functional evaluation of 3D printed prostheses are scarce since randomized controlled trials are not possible and only indirect data obtained in patients with previously implanted prosthesis substituted by 3D printed devices are available. Nonetheless, these preliminary reports in which pulmonary function tests, cardiopulmonary exercise tests or motion range capture studies are performed with reflective surface markers (optoelectronic plethysmography or photogrammetry) seem to reveal that 3D prostheses increase forced expiratory volume in the first second (FEV_1), abolish paradoxical movement in upper rib cage and increases synchrony between thoracic and abdominal movement compared to the preoperative settings, what seems to be promising outcomes (93-95).

Oncological outcomes

As previously said, the most common primary sternal tumor is chondrosarcoma and radical resection without adjuvant therapy seems to be associated with a good overall survival. After sternal resection in 89 patients, Marulli *et al.* (81) found a 5- and 10-year overall survival of 67% and 58% respectively, with a disease-free survival of 70% and 52%. Another recent series including a 64% of sternectomies performed for primary tumors recorded a 61% overall survival with a median follow-up of 24 months (82). The main prognostic factor for survival is radicality of resection with adequate R0 surgical margins (at least 3 cm) which translates into a rate of total and subtotal sternectomies reaching over 80% in some publications (42,83). Other prognostic factors such as histological low grading, younger age, diameter equal or less than 6 cm and no adjuvant treatment have also been pointed in other studies although these data should be interpreted with caution because the study population is small due to the low incidence of these type of tumors.

Survival is clearly worse for patients undergoing resection of purely metastatic disease compared to primary tumors or sternal involvement secondary to neighborhood diseases. Breast cancer is the most frequent secondary sternal tumor and surgery can offer a 5-year overall survival ranging 20% to 50% provided an R0 resection is achieved, although radical surgery does not appear to decrease recurrence rates. Metastasis from a source other than the breast result in the worst outcomes (less than 40% at 36 months and 0% at 5 years) (7,36,82) and although limited data are available on these cases, the radicality of the resection neither seem to modify global survival nor the recurrence rates, so it is likely that a conservative approach will be more appropriate (83).

Conclusions

Sternal resection and reconstruction is a rare but frequently extensive surgical procedure with important anatomical and functional implications. Therefore, an adequate preoperative evaluation followed by an adequate planning of the reconstruction is essential to ensure good oncological and functional results. In a clinical setting with many available reconstructive techniques and in the absence of high-quality data comparing them, specific recommendations for particular cases are difficult to make, making clear the need for more multicenter, comparative studies.

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