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REVIEW ARTICLE

New perspectives in prosthetic reconstruction in chest wall resection

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Abstract

The extension of chest wall resection for the treatment of primary and secondary tumours is still widely debated. The reconstructive strategy after extensive surgery is challenging as well as chest wall demolition itself. Reconstructive surgery aims to avoid respiratory failure and to guarantee intra-thoracic organs protection. The purpose of this review is to analyse the literature on this issue focusing on the planning strategy for chest wall reconstruction. This is a narrative review, reporting data from the most interesting studies on chest wall demolition and reconstruction. Representative surgical series on chest wall thoracic surgery were selected and described. We focused to identify the best reconstructive strategies analyzing employed materials, techniques of reconstruction, morbidity and mortality. Nowadays the new "bio-mimetic" materials in "rigid" and "non-rigid" chest wall systems reconstructive represent new horizons for the treatment of challenging thoracic diseases. Further prospective studies are warranted to identify new materials enhancing thoracic function after major thoracic excisions.

Keywords Chest wall tumors · Chest wall reesections · Prosthesis

Introduction

The chest wall (CW) is a complex structure, including a bony skeletal part (the rib cage) and a muscular as well as a fascial parts. The CW has important functions including the protection of thoracic (i.e., heart, lungs) and abdominal (i.e., liver and spleen) organs, stabilizing the actions of the shoulder and arm, and promoting respiratory movement. CW can be affected by several types of tumours. CW malignancies might be classified into primary (tumours that originate in the chest wall) and secondary tumours. Those latter might spread (metastasize) to the chest wall directly from surrounding organs or due to haematogenous dissemination [1]. In the field of surgical oncology, resection of the CW represents a challenging procedure.

It is well-known that surgical treatment of CW malignancies might require wide radical resection with the aim to achieve free margins. In most cases, those wide resections are associated with complex reconstructions through the adoption of prosthetic materials (e.g., synthetic or biological/cadaveric) and/or myocutaneous or muscular flaps [2–5]. Furthermore, several authors reported that the extension of CW resection may impact negatively respiratory mechanics [6–9]. Planning the correct reconstruction strategies is necessary as well as planning the resection phase to preserve lung function [10–20].

According to the principles of "biomimesis", the ideal prosthesis should respect and reconstruct the original anatomy and the organ function. The major difficulty is to preserve a functional and rigid chest wall structure, which is a protective system able to create a negative pressure to breathe. A perfect reconstruction is rigid and flexible at the same time. In addition, materials used for CW reconstruction should undergo these rules: malleability, radiolucency and inertness. Specifically, it should guarantee the protection of the mediastinum and lungs, with adequate biocompatibility anatomical structures (without allergies or inflammation/reject from foreign material) and it should allow physiological pulmonary expansion. According to these principles, a variety of prosthetic materials (combined or not with a multitude of reconstructive approaches) have been proposed in literature, with different postoperative outcomes. In this narrative review, we performed a critic analysis of the literature to assess the pros and cons of various reconstructive strategies, especially after extensive and challenging CW resection. Data on the most pertinent studies on this issue were

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collected and discussed [1–75]. Hence, we describe surgical techniques focusing on various materials that might be used during the reconstructive phases. Moreover, we focused our discussion on postoperative outcomes, including recovery, morbidity, and anatomical/functional modifications.

Surgical technique

CW resection is required to treat patients with a primary or secondary tumour invading the CW. Other indications for resection range from non-oncological conditions (being radionecrosis the most common disease) to a variety of congenital malformations. A specific approach to CW resection and subsequent reconstruction begins with the assessment of the size and location of the defects, the depth of tumoral invasion, the quality of adjacent tissues, the prognosis of disease (and related expected long-term and disease-free survival) and the need for curative or palliative surgery. In this scenario, the most used reconstructive technique is a combination of mesh and muscular flaps. The rigid reconstruction (with or without myocutaneous flap) is required according to the surgeons' experiences. It can be employed for repairing large CW defects usually more than four ribs, and more frequently in anterior and sternal defects, with the aim to avoid flail chest and to decrease the post-operative non-invasive ventilatory support [7, 21–24]. Given the presence of trunk muscles and scapula, posterior and apical defects as well as those near the spine can be reconstructed without the application of rigid prosthesis. In selected cases, limited anterior defects can be covered with pectoralis muscle, with or without soft reconstruction. After the first reports on metal prosthetic application [25, 26], many new materials have been developed: biologic, alloplastic and synthetic [43–48, 53]. Methyl-methacrylate (MM), polyglactin (Vycril), polypropylene, polytetrafluoroethylene (PTFE), titanium represent the most common synthetic materials employed in clinical practice.

Materials: soft vs. rigid

The meshes and patches are easy to deploy, handle and anchor to adjacent ribs around the defect. They can be permeable or impermeable to fluid and applied using a single or double layer to guarantee further resistance. The Vicryl and Polypropylene are the most common flexible materials used in those patients with a high risk of infection because of the extreme permeability to fluids that avoids the occurrence of seroma. Contrariwise, although its worldwide use, PTFE is a waterproof non-absorbable material associated with a higher risk of infection (ranging from 4.3% and 9% in the literature) [48, 49, 60].

Concerning rigid reconstruction, Methyl-methacrylate (MM) is one of the most common materials utilized especially after extended CW resections, since it allows increased CW stability as well as a mechanical and protective function. Also, it can be sandwiched between two layers of other meshes (i.e. polypropylene, Surgimesh-PET, etc.) [8, 27, 28]. This "in situ" modeled technique has the advantage of rigid reconstruction that avoids paradoxical motion. On the other hand, its extreme rigidity is associated with higher rates of seromas, hematomas, infections, fracture, and risk of prosthesis removal (up to 5% of patients) (8; 23).

We presented in 2011 our experience about Methyl-methacrylate "rib-like" technique [68] modelling the two cyanoacrylate resins on a chest aluminium cast obtained from a plaster mould reproducing costal arches and the sternum.

Materials: osteosynthetic materials

Ideal characteristics for CW rigid materials include high-tensile strength and resistance, good biocompatibility and bio-incorporation, as well as low infection rates. In this setting, titanium is a solid highly biocompatible metal, inert, resistant to infections and fully adaptable to the shape of CW. For these reasons, it is considered a better metallic implant system in surgery compared to ceramic [72] and stainless materials and can be used with excellent results both in oncological and non-oncological diseases (i.e., traumatic or malformity conditions) [63, 65, 67]. Specifically, there are two different systems for titanium implantation. The first refers to the application of titanium bar on the titanium clips screwed in ribs or to the titanium bridge bars directly screwed in ribs. In this context, Berthet et al. described the association of this system with PTFE mesh and reported a significant failure risk (44%) [29, 30]. Similarly, Fabre et al. experienced implant failure in 44% of cases (83.3% for broken mesh and 16.7% for displaced prosthetic replacement); anterior defects and more than 3 implants are associated with significant surgical failure ($p = 0.02$) [73].

Materials: bioscaffolds

Nowadays, a great interest is focused on biological tissues such as those derived from the cadaveric human dermis, from porcine small intestine submucosa, from the porcine dermis and bovine pericardium matrix [31–38, 55]. These bioprosthetic meshes are composed of decellularised scaffolds and matrices that allow fibrous tissue ingrowth. To avoid rejection or digestion [32], nearby vascularized tissues or mhe yo-cutaneous flaps are necessary. Other advantages of these scaffolds are the low risk of infection, and the possibility to employ in case of infection after rigid mesh reconstruction [33]. However, they should not be used for the reconstruction of large sternal resections (including bilateral costal cartilages and ribs) because there is an increased risk of anterior paradoxical motion and respiratory compromise [55]. Similarly to the titanium system, another limitation is the high cost. In selected cases, the cadaveric cryopreserved sternal allograft (combined with titanium bars) for sterno-chondral replacement showed encouraging results with a very low rate of respiratory impairment or flail chest [36, 66]. However, the possible further applications of these new biomaterials should be better addressed in future prospective studies.

Materials: flaps and tissue engineering

As reported by the majority of studies, muscle, myo-cutaneous and omentum flaps play a significant role in the reconstructive setting after CW demolition. The vascularized flaps optimize the intake of the prosthesis, reduce the risk of wound infections, obliterate the dead space (avoiding the occurrence of seromas), cover and separate the synthetic materials reducing the risk of prosthesis removal [39] The choice of flap depends mainly on the type of resection and on the defect's position. The greater omentum plays a crucial role in reconstruction especially in the contaminated field because it can be transposed in any CW location, supporting leukocyte and blood cells supply. On the other hand, its use may be associated with significant intra-abdominal morbidity such as abdominal and trans-diaphragmatic hernia. Furthermore, to prevent postoperative complications, attention should be paid to preserving the arterial blood supply to avoid excessive tension, which may be related to necrosis, retraction of the flap or instability of the overlying skin graft [18].

A new engineered method described to fill up the dead space and to improve the intake of the prosthesis is the implantation of stem adipocyte cells on the inner surface of the mesh. This method implies the creation of a new tissue that improves the vascularisation of in vivo implants. Other interesting results were reported by applying hybrid scaffolds composed of soft or bone/cartilagineous tissues derived from engineering amniotic mesenchymal stem cells [34, 35, 39, 43]. These specific materials lead to an enhanced recruitment of hematopoietic cells, supporting the regeneration of the defect site. Furthermore, these hybrid scaffolds are stable, flexible and easy-to-use and can be molded to the shape of the defect with good results. We deem that these interesting features will be employed to develop future clinical applications (Fig. 1).

Postoperative outcomes

CW is a complex and challenging procedure. The risk of developing morbidity and mortality is not neglectable after complex CW resection and reconstruction. In the present chapter, we discussed the risk prevalence of surgery-related complications and their impact on patients' recovery. Additionally, we discussed how CW resection/reconstruction affect anatomical and functional features of the CW.

Outcome: overall complications and risk of prosthetic removal

Despite the advances in surgical techniques and prosthetic materials, general complications after CW resection/reconstruction are common, occurring in 24% to 46% of patients (Table 1). They are related to major surgery such

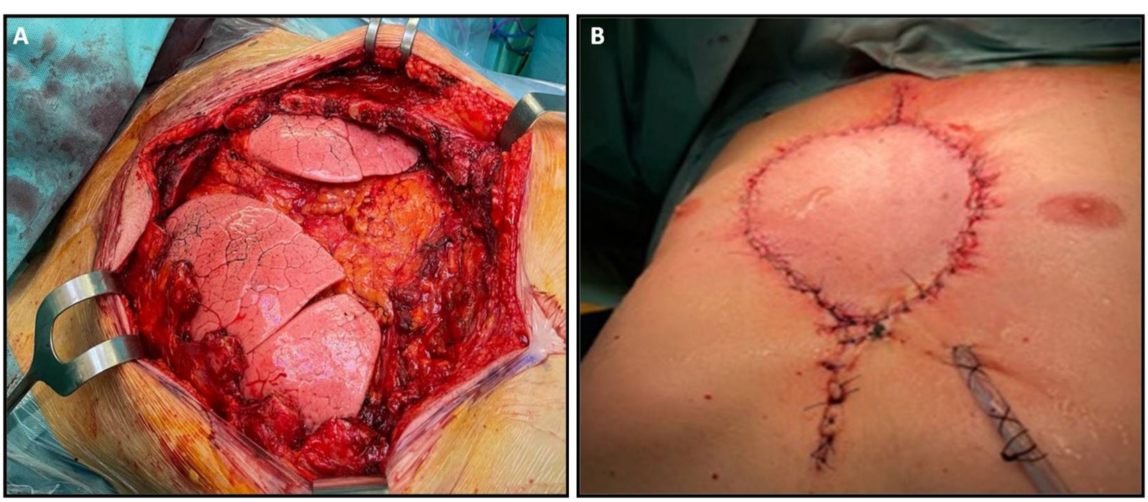

Fig. 1 **A** Intra-operative extended resection; **B** Result of the reconstruction with prosthesis and myocutaneous flap at the end of surgery

Table 1 Main studies investigating chest wall resection and reconstruction

Author, date and country, Study type, Level of evidence	Patient group	Outcomes	Key results	Comments
Arnold PG, 1984, Rochester, Restrospective study Level of evidence 4 [51]	100 patients with chest wall tumors	142 muscle flaps 29 Prolene mesh 11 Autogenous ribs	30-days-Mortality: 1% Late mortality: 24% Remove prosthesis: 2%	Adequate resection and dependable reconstruction are the mandatory ingredients for successful treatment
Pairolero PC, 1985, Rochester, Retrospective study Level of evidence 4 [51]	100 patients with chest wall tumors	57 prosthetic material 11 autogenous ribs 100 muscle transpositions	30-days-Mortality: 1% Overall complication: 9%	Aggressive resection for chest wall tumor with reliable reconstruction can be accomplished safely and that early wide resection is potentially curative treatment
Lampl LH, 1988, Augsburg, Retrospective study Level of evidence 4 [53]	302 patient retrieved, 25 of these with chest wall resection	10 not reconstructed, 10 Gore-Tex patch 2 mm-thick 2 Vycril mesh 3 Marlex mesh	Infection prosthesis 6% Major respiratory complication 4% 30-days-Mortality 4%	Goretex patch combines advantages such as available in every required size, really good proof of tension, tightness for air and fluids in contrast to meshes, good incorporation without problems but not in case of infections
McKenna RJ, 1988, Texas, Retrospective study Level of evidence 4 [61]	112 patients enrolled, 82 patients underwent to chest wall reconstruction especially for breast cancer and sarcoma	8 Methy- Methacrilate + Marlex mesh 56 Marlex mesh alone 4 Dexon mesh 30 non recostructed	Perioperative-Mortality 3% Minor wound complication 20% Major wound complication 5%	Prosthesis should be adequate-sized chest cavity. For posterior defects, more than 5 ribs, it is necessary a patch to prevent the catch of the scapula. For metastatic disease CWR/R is indicated for local control of symptoms. For Lung cancer N0, CWR/R offers 30–40% chance of 5-year survival
Arnold PG, 1996, Rochester, Retrospective study Level of evidence 4 [4]	500 patients enrolled, 184 underwent to chest wall reconstruction with a prosthesis	116 Polytetrafluoroethylene (PTFE) soft-tissue patch 55 Polypropylene mesh 13 Autogenous ribs	No data about overall complication and prosthesis removal 30-days-Mortality: 3% Late mortality (> 55 months): 47.2%	407 patients underwent 611 muscle flaps for the reconstruction of the integument; omentum is the best friend during reconstruction with infection fields
Deschamps, 1999, Rochester, Retrospective study Level of evidence 4 [38]	197 patients enrolled for chest-wall resection and reconstruction for chest wall malignancies, lung cancer, breast carcinoma	64 Polypropylene mesh 133 PTFE mesh	Overall complication: 46,2% Prosthesis removal: 2% * Mortality: 4.1%	A slight difference exists between the two types of reconstruction; Planning surgery with a "fallback or secondary procedure"
Mansour KA, 2002, Atlanta, Retrospective study Level of evidence 4 [3]	200 patients with malignancies of the chest wall enrolled, 93 chest wall reconstruction with a prosthesis, 43 primary reconstruction	49 Prolene mesh 21 Marlex mesh 11 Methyl methacrylate sandwich 11 Vicryl mesh 1 Polytetrafluoroethylene (PTFE)	Overall complication: 24% (including pneumonia, ARDS and flap loss) 30-days- Mortality: 7%	113 procedure of muscle flaps for the reconstruction of soft tissue The key to a successful outcome is a coordinated effort by the surgical teams (thoracic & plastic teams)

Table 1 (continued)

Author, date and country, Study type, Level of evidence	Patient group	Outcomes	Key results	Comments
Chang RR 2004, New York, Retrospective study Level of evidence 4 [15]	113 patients enrolled 62 underwent prosthetic chest wall reconstruction especially for breast cancer and sarcoma	62 Marlex-mesh and Methyl-methacrylate as a sandwich	Overall complications: 17.6% Prosthesis removal: 8% 30-days- Mortality: 4.9%	157 muscle flaps used to cover soft tissue loss. Safety and reliability of flap reconstruction of chest wall defects. Reconstructive algorithm elaborated
Doddoli C, 2004, Marseille, Retrospective study Level of evidence 4 [65]	309 patients with large chest wall defects -> repaired in 84 cases with prosthesis	Flexible mesh in 68 cases; Marlex in 14 cases Gore-Tex in 2 cases Muscle transpositions were associated in 3 cases	Overall complications: 32.7% Mortality: 7.8% Postoperative mortality rates associated with lung resection 5.7% for lobectomy, 33.0% for bilobectomy 12.7% for pneumonectomy	Multivariate analysis: male, sex, and bigger tumor size as independent indicators of poor prognosis in stage IIB patients En-bloc resections provided higher 5-year survival rates when compared with extrapleural resections
Weyant MJ, 2006, New York, Retrospective study Level of evidence 4 [23]	262 patients enrolled, 209 underwent prosthetic chest wall reconstruction for NSCLC, breast cancer, sarcoma	112 Polypropylene mesh/ methylmethacrylate composite (MMM) 97 PTFE or Polypropylene mesh (PPM)	Overall complications: 33.0% Prosthesis removal: 4.3% 30-days-Mortality: 3.8%	MMM prostheses are associated with a considerable number of wound complications. Respiratory failure continues to be the main source of respiratory complications; pneumonectomy combined with chest wall resection had a mortality rate of 44% Rigid repair provokes less pulmonary problems
Lans TE, 2009, Rotterdam, Retrospective study Level of evidence 4 [56]	220 patients enrolled for CWR/R	Vycril mesh Polyurethane Homologous dura mater, Double layer polypropylene-polytetrafluoroethylene mesh	Moderate complication: 15% Serious complications: 19% 30-days-Mortality: 2.3%	Ulcerating tumors or radionecrotic areas are at risk for post-reconstructive wound healing failure. Patient selection, surgical techniques, and the prosthesis of choice should be subject of careful consideration to prevent postoperative complications
Girotti P, 2011, Milan, Retrospective study Level of evidence 4 [27]	101 patients enrolled for sternal tumours resection/reconstruction	52 Soft reconstructions (Vicryl, Marlex, Gore-Tex, Prolene mesh) 27 Rigid shield reconstruction (Plate of methacrylate + silicone + Teflon or Cyanoacrylate shield + Marlex mesh) 22 Rib-like reconstruction	Overall complications: 22.7% Prosthesis removal 6.9% 30-days- Mortality 0.9%	The rib-like technique is feasible and safe with good integration with surrounding tissue; the choice of reconstruction depends on surgeon preference; muscular flap use is necessary to cover and prevent prosthesis removal

Table 1 (continued)

Author, date and country, Study type, Level of evidence	Patient group	Outcomes	Key results	Comments
Miller DL, 2013, Atlanta, Retrospective study Level of evidence 4 [55]	213 patients analyzed for CWR/R, 25 underwent to protesic reconstruction for maglignancies and benign desease	11 bovine pericardial patch + PLA bars 10 bovine pericardial patch alone 4 PLA bars alone	Overall complications: 24% Prosthesis removal: 12% Mortality: 0%	Biomaterials can be used in contaminated cases but should not be used for large sternal resections, which include bilateral costal cartilages and ribs because increased risk of anterior paradoxical motion and respiratory compromise
Leuzzi G, 2015, Rome, Retrospective study Level of evidence 4 [7]	175 patients enrolled (49.1% benign tumors, 50.9% malignant tumors) for CWR/R	39 cases stabilized with non-rigid prosthesis (Vycril mesh 8; Goretex mesh 31)	Overall complications: 12.6% 30-days- Mortality 0.6%	CW stabilization with non-rigid prosthesis is associated with a low rate of complication and causes only moderate changes in pulmonary function. Male sex, Lung resection, Rib resection, Use of prosthesis, secondary malignant tumors were significant predictors of higher stay

PTFE polytetrafluoroethylene, *ePTFE* expanded-polytetrafluoroethylene, *ARDS* acute respiratory distress syndrome, *NSCLC* non-small-cell lung cancer, *CWR/R* chest wall resection/reconstruction, *PLA bars* polylactic acid bars

*All patients who received polypropylene mesh as haemorrhages, atrial fibrillation, deep vein thrombosis, renal failure and, respiratory complications depending on either a poor pulmonary toilet or paradoxical respiratory movement (flail chest). Specifically, as already described in the literature, main lung complications are respiratory failure, pneumonia and acute respiratory distress syndrome (ARDS) (46; 3) with related long hospital and ICU stay as well as increased mortality rate (ranging from 0% to 15.3% of patients, Table 1). Although data on mortality are still debated, generally it has been reported a worse outcome in the case of lung resection associated with CW surgery. In this setting, Weyant et al. [23] reported a mortality rate of 44% in patients undergoing CW resection and combined pneumonectomy. Similar results were reported by Doddoli et al. [65] in patients undergoing lung and CW surgery (mortality of 5.7% for lobectomy, 33.3% for bilobectomy and 12.7% for pneumonectomy). On the contrary, a multicentre retrospective study on CW resection [54] evidenced an acceptable mortality rate after pneumonectomy (2.9%). According to these interesting data, it has been suggested that a careful knowledge of comorbidity and accurate cardio-respiratory assessment can help to identify patients with a higher risk for unfavourable outcomes. In addition, as already reported by other authors, another critical factor is the experience of the institution in dealing with such complex surgery [20].

In the literature, other common morbidities are those related to local complications (from 4 to 20% of cases) such as wound infection, seroma, flap hematoma or necrosis, wound erosion, and prosthetic dislocation, erosion or infection [48, 49, 56, 60]. General management implies conservative treatment (such as antibiotics, Vacuum Assisted Closure Therapy and positioning of silicone tube for suction) as well as surgical procedures (debridement of necrotic/infected tissue, prosthetic removal). Surgical treatment remains the main option in case of prosthetic dislocation/rupture/erosion. These complications range from 2 to 44% in different series and are more often are associated with the use of MM and PTFE (Table 1) [8, 9, 14, 15, 27, 46, 51, 52, 55, 72, 73]. Numerous studies tried to identify possible predictors of prolonged hospital stays and morbidities. Although it is hard to analyse and stratify the risk for such a heterogeneous population (different histologies and techniques for CW resection/reconstructions), significant predictors of local complications are male gender, large tumour size, associated lung resection, large resection area, use of prosthesis, R1/R2 resection and secondary malignant tumours [7, 14, 54, 64].

Outcome: lung and spine anatomical/functional modifications

After CW resection/reconstruction, data on lung function compromise are still debated in the literature. Some authors [7] found no significant difference in pre/post-operative force expiratory volume (FEV1) values among patients undergoing CW reconstruction with or without a synthetic prosthesis. Similar results were reported by other authors [8] that treated patients with (or without) a non-rigid prosthesis [48, 50], also in terms of postop ventilation need support. Otherwise, some authors [63] evidenced up to 11% of partial paradoxical movement with non-rigid reconstruction, although it did not impair significantly respiratory function.

In the literature, very few studies reported data on anatomical change after CW surgery. In our experience on extended CW demolitions/reconstructions, we observed modification in the shape and in the external appearance of the reconstructed hemithorax in all patients, a worsening of left-convex scoliosis (50% of cases) and a progressive approximation of the prosthesis to the mediastinum (25% of patients) [28, 69, 70]. Concerning the quality of life, no patients experienced chronic chest pain, upper girdle dysfunction, shortness of breath or digestive disorders, suggesting a specific body adaptation after CW reconstruction.

Conclusion

This is a narrative review evaluating techniques for CW demolition and reconstruction. CW surgery should be carefully planned considering histology, previous treatment (chemo/radiotherapy), size of resection, experience in the application of specific prosthetic materials and expertise in managing myo-cutaneous/muscolar flaps. A better local control results in improved overall survival in cancer patients. Optimal oncological and functional outcomes may be achieved through a combination of multimodal therapies and planned surgical reconstructive strategies, especially in experienced centres**.** The discovery of new “bio-mimetic” materials and more appealing techniques has allowed to treat larger tumours in more challenging patients who could not be treated at all in past years. The major extended CW resections (including combined multi-organ excision) should be performed only in institutions with a dedicated multidisciplinary team with expertise in managing general and specific postoperative complications through the use of conservative (e.g., advanced medications non-invasive ventilation) and more aggressive approaches (e.g., re-operation for prosthesis removal, prosthetic re-implant, re-harvesting/re-implant of myocutaneous flaps). The thoracic prosthetic reconstruction should combine flexibility, protection and bio-compatibility, with high bio-compatibility and low risk of infections and failure [36, 75] Actually, bio-scaffolds represent the future step for auto-regeneration, however, the “classical” (rigid or soft) prosthetic reconstruction is still the mainstay in this kind of surgery. Given the high heterogeneity in terms of patients’ features and surgical techniques, we recommend the need for further comparative and multicenter studies to better understand the outcome differences between”past” and “new” materials and their application.

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