Review Article

# Chest wall reconstruction, prosthesis and allografts: a narrative review

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**Background and Objective:** What is the best material in the case of prosthesis used to replace major chest wall resection is still unknown. We reviewed most significant literature focused on the type of prosthetic materials available by highlighting their relative pros and cons.
**Methods:** We reviewed most significant articles, including clinical results of relevant case series (retrospective studies), published in English in the last 23 years: PubMed, Embase and Scopus databases were used in our search in the period between the 1st January 1999 and 31st December 2022.
**Key Content and Findings:** Overall, our literature review revealed lack of uniformity or conformity in the surgical strategies described for chest wall reconstruction with no internationally accepted standard in terms of decisions and optimal prosthetic materials and type of prostheses (soft, rigid, biological). Despite the increased interest in chest wall reconstruction, we observed a general lack of substantial prospective and multicentric studies. Likewise, there are not substantial data which may guide to the choice of optimal prosthetics in terms of characteristics and biocompatibility.
**Conclusions:** A variety of materials are available for reconstruction, including synthetic and biological meshes, flexible and rigid patches, and metal osteosynthesis systems. The material chosen should be optimized to each patient and damaged tissues to be restored. Prospective and multicentric studies are necessary to address current limits in this surgical field.

**Keywords:** Chest wall; resection; reconstruction; prosthesis; allograft

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## Introduction

Major chest wall replacement after full-thickness resection still remains one of the most challenging procedures for thoracic surgeons (1-3). Early pioneers of thoracic reconstruction used pedicled latissimus dorsi flap to cover chest wall defects (4); earliest technology did not allow the production and the implant of an effective and safe alloplastic or metal prosthesis. The first prosthesis only appeared after the advent of methylmethacrylate in the orthopaedic field in the 70s (5). Thoracic surgeons drew inspiration from orthopaedic materials to develop the first chest wall prosthesis to permit full thickness resections of ever greater size. In the following decades, chest wall

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**Table 1** Different types of material used for the chest wall reconstruction and stabilization in human classified in alloplastic/synthetic or bioprosthetic materials and their surgical performance (chest wall stability, organs protection, muscles function, risk of infection and customization from less to more)

| Synthetic materials | Chest wall stability | Organs protection | Muscles function | Risk of infection | Customization |
|---|---|---|---|---|---|
| Methylmethacrylate | +++ | +++ | – | ++ | + |
| Polyglactin (Vicryl, Ethicon, Inc., Somerville, NJ) | – | – | + | – | +++ |
| Nylon | – | – | + | + | +++ |
| Polypropylene (Marlex, Davol & Bard, Cranston, RI, and Prolene, Ethicon Inc, Somerville, NJ) | – | – | + | – | +++ |
| Polytetrafluoroethylene (Dualmesh, W.L. Gore & Associates, Flagstaff, AZ) | – | – | + | – | +++ |
| Silastic and Silicon | + | + | + | +++ | +++ |
| Titanium and steel | +++ | +++ | – | +++ | – |
| Polymethylmethacrylate | +++ | +++ | – | ++ | + |
| Bioprosthetic materials | | | | | |
| AlloDerm (LifeCell Corporation, Branchburg, NJ) | – | – | + | – | + |
| Cadaveric human dermis | – | – | + | – | + |
| Porcine dermis | – | – | + | – | + |
| Bovine pericardium | – | – | + | – | + |
| Bovine dermis | – | – | + | – | + |

reconstruction evolved significantly due to improved surgical techniques and availability of multiple synthetic materials (6). Despite the extensive literature available, there is no consensus regarding the optimal material and shape of prosthetics. The only agreement in the field is that "wide" skeletal resected specimen must be replaced by biological, alloplastic or metal prosthesis (7). We therefore focused not on the rules of "when and how" to replace rather on the type of materials available on the market and their specific positive and/or negative characteristics. Chest wall resection and reconstruction is still affected by a high respiratory morbidity and mortality, therefore the development of human rib replacement techniques have received significant attention for restoring the normal respiratory function and reducing the rate of postoperative complications (8-10). So far, the average rate of complications is between 24–46% of cases (~24% respiratory) (1-3,5,6).

An optimal prosthesis should have following characteristics (11-13):

(I) Maintenance of chest wall rigidity;
(II) Prevention of the herniation of the lungs;
(III) Maintenance of the chest volume to prevent dynamic impairment;
(IV) Avoiding the trapping of the scapula;
(V) Protection the underlying mediastinal organs;
(VI) Reducing the risk of local and systemic postoperative complications.

*Table 1* shows different types of material used for the chest wall reconstruction and stabilization in human classified in alloplastic/synthetic or bioprosthetic materials and their surgical performance (14-16). Despite different types of materials are available, the advent of 3-dimensional (3D) printing technology is pushing the use of custom-designed titanium or alloplastic implants for their excellent and fine native biomechanical behaviour and features (17-19).

A niche role is the reconstruction of the stern after sternectomy (due to postoperative infection and necrosis, after cardiovascular surgery) by using cadaveric chest wall specimen. However, cadaveric prostheses are not frequently used for chest wall stabilization and/or reconstruction,

**Table 2** The search strategy summary

| Items | Specification |
|---|---|
| Date of search | 1 March 2023 |
| Databases and other sources searched | PubMed, Embase and Scopus databases |
| Search terms used | Chest wall disease, chest wall resection, chest wall reconstruction, chest wall prosthesis, rigid and soft prosthesis, allograft, human and animal allograft |
| Timeframe | 1st January 1999 to 31st December 2022 |
| Inclusion and exclusion criteria | Inclusion criterica: full-text studies; single and multicenter study; English language; more than 5 patients; adults; speciment >5 cm and/or >4 resected ribs<br>Exclusion criteria: case report; pediatric patients |
| Selection process | Selection was conduced by two authors; duplicate titles were excluded; personal selection of the abstract based on inclusion criteria; personal selection of the article based on inclusion criteria |

in the case of post-traumatic chest wall instability or oncological resection, which is mainly due to scarce availability of the material and the problems related to organ retrieval (20-22).

Here we performed a comprehensive review of literature about chest wall prosthetics with an outlook to new materials and biological allografts, which are gaining interest in the field. We present this article in accordance with the Narrative Review reporting checklist (available at https://jtd.amegroups.com/article/view/10.21037/jtd-23-650/rc).

## Methods

This is a narrative review which focused on literature published from 2000 to 2023 years. We reviewed all articles, including clinical results of relevant case series in retrospective studies, published between the 1st January 1999 and 31st December 2022. Literature search was performed using the following MeSH terms: "chest wall disease", "chest wall resection", "chest wall reconstruction", "chest wall prosthesis", "rigid and soft prosthesis", "allograft" and "human and animal allograft". The PubMed, Embase and Scopus databases were used.

Publications of any type including case series, prospective observational studies, and randomized controlled trials were eligible for inclusion. Technical articles and case reports were excluded (i.e., with less than 3 patients). Abstracts of all studies were screened independently by two investigators. Duplicate references were removed by manual selection. Inclusion criteria were: English-language publications describing "large" chest wall resection and reconstruction (>5 cm and/or 4–5 ribs) with implantable materials for post traumatic deformities, benign or malignant tumors or chest wall growths in adult patients. Exclusion criteria were: paediatric patients, non-English language articles, cases of soft tissue resection only with no chest wall resection and reconstruction without the use of implantable materials such as primary chest wall repair or muscle flaps (*Table 2*).

Data extraction included study characteristics:

(I) Type of resection;
(II) Size of specimen;
(III) Type of reconstruction;
(IV) Overall early postoperative morbidity;
(V) Wounds infection rate;
(VI) Respiratory complication rate;
(VII) Overall early postoperative mortality.

## Discussion

Our literature review revealed a lack of uniformity or conformity in the surgical strategy described for chest wall reconstruction with no internationally accepted standard in terms of decisions (i.e., when to reconstruct with a prosthesis), prosthetic material and shape of the prosthesis (23-28). Despite the increased interest in the chest wall reconstruction, we observed a general lack of substantial prospective and multicentric studies. The majority of the articles refer to case studies with small case series (monocentric studies). Likewise, there are not substantial data that can confirm the superiority of a material over the others. It is also unclear when rigid reconstruction should be mandatory. However, recent studies, focusing on the mechanical behaviour of the chest wall, suggested that the localization of the defect/s is the most important factor to guide the decision-making process toward a soft or rigid reconstruction (7,18,29).

The following rules are usually accepted by most of the surgeons to evaluate the need for chest wall reconstruction (30,31):

- ❖ The use of rigid prosthetic materials is mandatory in the case of anterior/lateral defects with size >4–5 cm.
- ❖ The use of muscle flap or soft prosthesis is suggested in the case of lateral defect. Only defects with size >5–6 cm should be replaced with rigid prosthesis.
- ❖ And posterior defects may not require reconstruction when covered by the scapula without any risk of inward rotation or if stabilized by adjacent muscles.
- ❖ Partial sternal resection (<1/3 of the sternum) may not require rigid reconstruction.

Notwithstanding, an agreement about the optimal strategies to follow for chest-wall reconstruction, considering the defects type and position, is still missing. Yet, there are not preferred material for chest wall reconstruction while international certifications are missing for prosthetic materials (5). Therefore, the use of such materials is still considered as "experimental" and not included in any international guidelines.

In the last years, materials and reconstruction techniques have not substantially changed from the 90s, though postoperative complications have considerably reduced compared to case series prior to 2000s (*Table 3*) (1,7,11,14,24-26,29,32-34). Therefore, in our opinion, the substantial reduction in morbidity can be attributed more to increased skills of surgeons and improvement of postoperative/intraoperative management rather than the evolution of materials.

In the following chapters, we describe the various types of prosthetic materials for chest-wall reconstructions by highlighting pros and cons considering the kind and positions of thoracic defects (*Table 4*).

### *Soft prosthesis*

Soft implants were among the first to be introduced in thoracic surgery. The simplest solution to replace a defect of the chest wall after radical resection remains the use of mesh (alloplastic or biological) (30,33). Many soft materials have been developed over the last 30 years and were initially used for reconstruction of the abdominal wall. Nylon was available in the 70s, 80s and 90s and, currently, it has been replaced by more modern materials such as polypropylene, polyglactin and polytetrafluoroethylene, which are the most commonly used meshes in thoracic surgery (38,39). These materials have several important characteristics, i.e., (I) can be stretched uniformly and fixed to the costal free margins, allowing a uniform tension; (II) they allow muscle reattachment and repositioning; (III) they provide a barrier that prevents fluid and air moving between pleural and subcutaneous space; (IV) they offer a scaffold for the in-growth of regenerative connective tissue colonizing their outer and inner surfaces; and (V) they have an excellent patients' tolerance because. Several studies reported the use of non-absorbable synthetic woven meshes such as example, nylon, polypropylene, polyester and polytetrafluoroethylene, which were used folded and fixed to the edges of the ribs and fascia to cover the immediate surface of the chest wall defect. These non-absorbable prostheses have good integration with the surrounding tissues and, usually, do not cause pulmonary inflammatory reactions if in contact with the visceral pleural surface. Some authors reported an infection rate between 10% and 25% for synthetic meshes (implants removal: 10%) (25,38). Therefore, not all authors agree that soft implants have a substantially lower risk of infection than rigid implants.

In the case of patients with a high risk of infection and requiring small reconstructions, absorbable materials may offer a better compromise in terms of a lower risk of infection and sufficient stability of the chest wall. For example, during the resorption period, the VICRYL® allows the creation of a fibrotic scar with a consequent good closure of small defect without the risk of postoperative wound and chest wall infections. However, such prostheses suffer the limitation of not providing any protection of the mediastinal viscera (1,2). Besides, these "soft" meshes do not allow to restore rigidity of chest wall in the case of large lesions and therefore cannot be used to reconstruct large defects. In addition, soft prostheses cannot replace the normal curvature of the chest after major resections with a consequent volume reduction of the pleural cavity and an increased risk of postoperative respiratory distress (7).

### *Rigid prosthesis*

In case of rigid prostheses, the main materials used are polymethylmethacrylate/methylmethacrylate, titanium and steel.

Many others materials are available for chest reconstruction, such as carbon fiber molds, polyethylene,

 

**Table 3** Study details and quality assessment

| First author | Study type | Institution city, country | Study period | Study design | No. of patients | Matherial | Indication | ICU stay (days) | Morbidity (%) | Wound infection (%) | Pneumonia/ distress (%) | Mortality 30 days (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mansour (1) | Single | Texas, USA | 1975–2000 | Retrospective | 200 | Prolene mesh, Marlex mesh, methyl methacrylate sandwich, vicryl mesh, and polytetrafluoroethylene | Oncological, deformities | 5±9 | 15 | 5 | 6 | 7 |
| Girotti (7) | Single | Milan, Italy | 1980–2008 | Retrospective | 101 | Marlex mesh, methyl methacrylate sandwich | Oncological | 3.4 | 22.7 | 12.8 | 1.9 | 0.9 |
| Hanna (11) | Single | Montreal, Canada | 2003–2010 | Retrospective | 37 | Gore-tex, vicryl | Oncological | 6 | 24 | 13 | 21 | 0 |
| Leuzzi (32) | Single | Roma, Italy | 1998–2010 | Retrospective | 75 | Gore-tex, vicryl | Oncological | 2.4 | 31.7 | 22 | 9.1 | 0.6 |
| Billè (14) | Single | London, UK | 2010–2012 | Retrospective | 18 | Titanium | Oncological, trauma | 0.5 | 16.6 | 11.1 | – | 0 |
| D'Amico (33) | Single | Bergamo, Italy | 2005–2015 | Retrospective | 11 | Porcine dermis | Oncological | 2 | 45 | 27 | 9 | 0 |
| Lardinois (29) | Single | Bern, Swiss | 1994–1998 | Retrospective | 26 | Methylmethacrylate | Oncological | – | 23 | 8 | 8 | 0 |
| Weyant (34) | Single | New York, USA | 1995–2003 | Retrospective | 209 | Methylmethacrylate and polypropylene sandwich | Oncological | 7 | 38.4–27 | 7 | 3.1 | 3.8 |
| Daigeler (25) | Single | Bochum, Germany | 1995–2007 | Retrospective | 62 | Polypropylene | Oncological | – | 42 | 10 | 4.2 | 0 |
| Deschamps (24) | Single | Minneapolis, USA | 1977–1992 | Retrospective | 197 | Polypropylene, polytetrafluoroethylene | Oncological | 2 | 46.2 | 4.6 | 24.4 | 4.1 |
| Salo (26) | Single | Helsinky, Finland | 1997–2015 | Retrospective | 36 | Polypropylene, polytetrafluoroethylene | Oncological | – | 35 | 15 | – | – |

**Table 4** References for different prosthetic materials

| Type of matherials | Ref. |
|---|---|
| Synthetic materials | |
| Polytetrafluoroethylene | (29,32,34) |
| Polymethylmethacrylate and its composites | (29) |
| The titanium alloy Ti-6Al-4V | (14,15,35) |
| Stainless steel AISI 316L | |
| Bioprosthetic materials | |
| Bovine pericardium | |
| AlloDerm® | |
| Porcine dermis | |
| Cadaveric human dermis and bones | (36,37) |

aluminum ceramic mold. However, despite these materials have been used by numerous centers there is a substantial lack of scientific articles in the last 23 years of literature which met our inclusion criteria.

An advantage of using rigid prostheses which reproduce the physiological curvature of the ribs, is the possibility to overcome some problems afflicting soft patches when used to replace extensive anterior and lateral chest wall defects, by reducing the risk of respiratory distress resulting from paradoxical movements and chest deformities (5,29,40).

### Methylmethacrylate and polymethylmethacrylate

Methylmethacrylate and polymethylmethacrylate are usually placed between two layers of the mesh to strengthen the rigidity of the reconstruction. Their use was introduced at the end of the 70s, in the orthopaedic environment as cements for hip prostheses. Since 80s, for many years this material has been the only available choice to reconstruct the sternum, ribs and chest wall, entirely or partially (40). The main problem of the methacrylate is the hardening proceeding of this plastic material. The union of the two components, that allows the formation of the plate, drives into an exothermic reaction that determines high temperatures and this obliges the surgeon to create and fit the prosthesis on the back table. For this reason, some authors reported some difficulties in producing an optimal shape that can be perfectly integrated with the chest wall defect. It should be also noted that methacrylate cannot be easily re-shaped afterwards and, if broken, produces sharp edges that can damage nearby organs. Therefore, these methacrylate-based prostheses cannot be easily customized (40,41). Other limitations of using methylmethacrylate included (I) low permeability to fluids, with a consequent augmented risk of postoperative seromas and infections, and (II) an excessive chest wall rigidity, with consequent increased pain (27,34,41). However, further data are needed to better assess these negative feature of the methacrylate and estimate postoperative complications rate (such as prosthesis dislocation or infection).

Such limitations prompted some authors in the mid-90s to propose a prosthesis that better reproduced the shape of the ribs allowing free intercostal spaces to facilitate the flow of biological fluids. Such approach is based on three main principles (16,42):

(I) To reconstruct the entire sternochondral plate;
(II) To reproduce the sternocostal joints in order to maintain permeable intercostal space.

By following this strategy, wound complications were reduced from 30% to 10% at 90 days and the removal of the prostheses was been reported in only ~5% of patients (5,34). Nevertheless, several authors have reported excellent results in terms of maintenance of respiratory capacity, with very low rate of early morbidity/mortality, even after major chest wall resections (1,24,30,34). The majority of authors agree, independently of the shape, that the complete coverage with viable soft tissue of the plastic materials is an essential step to minimize the risk of local complications after chest wall reconstruction (43-47).

Although the change of the shape of these prostheses has substantially reduced the risk of infection associated with methylmethacrylate, the excellent resistance of this material limits its adaptability to chest wall shape that occurs physiologically after major thoracic resections, especially those associated with pulmonary resections (40). Therefore, after chest wall reconstruction with methacrylate plates there still remains a high risk of dislocation or rupture of the prosthesis (32,42).

The development of new plastic materials to produce ever more elastic and light moulded prostheses is thus paramount. Such materials will improve the comfort and reduced the risk of dislocation. 3D printed prostheses using these low-cost plastic materials with mechanical strength similar to native ribs, could play an important role by increasing also the long-term compatibility with the native chest.

### Titanium

Titanium is an ideal prosthetic material which is biologically inert, highly biocompatible and diamagnetic.

The reconstruction of large portions of the chest wall requires extremely complex prostheses or different types of simple single bars. The main problems of complex titanium prosthesis are the excessive weight, the limited possibility of customization during surgery, and the high cost of production. Such problems have contributed to reduce the probability of using complex titanium prosthesis. However, simple titanium bars are still the most used fixation technique after trauma: they are low cost, well malleable and easy to customize during the operation (48-50).

Since 2000s, titanium proved to be the best material for prosthetic reconstruction in maxillofacial and orthopaedic fields. Some authors proposed also to use titanium prosthetics in the thoracic area with new dedicated titanium plates systems for the treatment of the chest wall diseases (14,15). Preformed titanium bars previously used in orthopaedic environments were initially used and then, starting from the first experiences, developed to create custom-made thoracic prostheses dedicated to the reconstruction of the ribs and sternum (i.e., STRATOS® system) (51,52). More recently, 3D titanium prostheses were employed for chest wall reconstruction after oncological demolition as well as for stabilization of the ribs after trauma (18). Currently, several types of ribs fixation systems and titanium bars were proposed in case of chest wall trauma. The Borrelly steel staple-splint system was the first system introduced in the 90s and it consists in rigid titanium bars that could be fixed on the ribs by steel clips. This system was very popular though with several problems associated included the excessive weight of the system and the difficulty of application (53). The STRATOS® system could be considered as an evolution of the Borrelly steel staple-splint system (by reducing the weight and short learning curve) (51,52). The MatrixRIB® and MDF® Medica devices use a comfortable remodelable bar with holes for screws to secure the bar to the ribs or to the sternum. This system has its major implication in the stabilization after traumas but some authors started to use similar approaches also in the case of chest wall replacement after oncological resections (54) and in combination with soft meshes.

There is also a substantial agreement that titanium systems represent a better solution in the reconstruction of large full-thickness defects (14,18,52), which allow to restore the rigidity of the thoracic cage and prevent respiratory and infective complications. Indeed, few complications, such as plate fracture, bar dislocation and thoracic pain, were described for this material (50).

However, in the case of complex and big prostheses, titanium material may suffer of the following problems: (I) a high cost of production (3D prosthesis); (II) the difficulty of fixation to the edges of resection (54). Therefore, many authors suggested that reconstruction of complex chest wall defects will require titanium prosthesis combined with synthetic, biological, or titanium meshes, and various muscle flaps, in order to substantially reduce the weight and to facilitate fixation of the prosthesis to the costal edges (35,55,56).

Most of the complications when using titanium prothesis come from case series of patients undergoing fixation of post traumatic rib fractures. Few postoperative complications data are available for the titanium prosthesis after oncological resections. Bar fracture rate varied from 0 to 11% in some series (57-59). Plate dislocation frequently is due to mismatch between the screw length and rib thickness, or to the destruction of the bone threads that lock the screws into the rib, due to repeating re-drilling in the same hole (60).

### *Biological prosthesis*

Biological prothesis were developed in order to increase the biocompatibility of the material while offering the same characteristics of traditional prosthetics in terms of biomechanical properties (22). For example, decellularized extracellular matrix (ECM) scaffolds (e.g., cartilages) offer the advantage of supporting cellular repopulation and revascularization when incorporated into the native tissues (22). Over the past decades, both human and porcine decellularized ECMs were developed to fulfill the need for complex chest wall reconstruction (20,21,60). Yet, the use of allograft transplantation such as bone grafts for anterior chest wall reconstruction after sternectomy was proposed to provide with a structure for growth and differentiation of osteoprogenitor cells, to rebuild the skeletal parts and restore structural integrity of the chest wall (61). A limitation of this approach can be certainly the amount of bone harvested from the donor which might be problematic in the case of large chest wall defects. An interesting field of research applied to biological prothesis, is the use of biomimetic materials which imitate both skeletal and non-skeletal tissue, and integrate both inorganic and organic scaffolds with the use of mesenchymal stem cells (MSCs). Bushmann *et al.* showed in a preclinical research study that poly(lactic-co-glycolide)/amorphous calcium phosphate (PLGA/aCaP) (62) mesh is an ideal biodegradable scaffold for the growing and differentiation of mouse adipose tissue-derived adult stem cells (ADSCs). After the integration of cell-seeded scaffold in a mouse model with viable immune system, a complete bio-integration with neovascularization, ECM deposition and recruitment of $CD45^{+}$ hematopoietic cells which supported the regeneration process was observed (62). Importantly, the combination of cellular therapy with biomimetic scaffolds showed that MSCs are capable to significantly dampen inflammatory response after grafting by favouring the switching of macrophage to the immune tolerant M2 polarization (62). M2 macrophages produce several components of ECM as well as angiogenic and chemotactic factors, which promote wound healing and favour the regeneration of the damaged tissues (61). MSCs exert several immunomodulation functions, e.g., suppress T-cell proliferation, inhibit dendritic cells antigen presentation and activation of NK-cells. Several soluble factors were described to be released by MSCs which have immunomodulation properties, such as transforming growth factor-β1 (TGF-β1), prostaglandin E2 (PGE2), hepatocyte growth factor (HGF), indoleamine-pyrrole 2,3-dioxygenase (IDO), nitric oxide (NO) and interleukin-10 (IL-10). Likewise, direct cell-to-cell contact is another mechanism used by MSCs to inhibit inflammatory response (63).

## Conclusions

Overall, we can draw the following conclusions:

- ❖ Despite improvements in surgical approaches and prostheses, there is a complete lack of standardization of methods without any clear guideline regarding the materials to be used in the different cases of reconstruction.
- ❖ A variety of materials are available for reconstruction, including synthetic and biological meshes, flexible and rigid patches, and metal osteosynthesis systems. The material chosen should be optimized to each patient and to defects being reconstructed.
- ❖ The prosthetic materials currently available for use in humans demonstrate optimal mechanical behaviour in terms of resistance and organ protection. However, it is not easy to translate experimental results into the clinical setting.
- ❖ Careful sizing and implantation can result in tight closure, thereby minimizing billowing and paradoxic motion with respiration, often with minimal effect on pulmonary function. If implanted carefully, these defects can be reconstructed with minimal complications and low rates of prosthesis removal.
- ❖ A systematic review of current literature and of the last three decades is strongly recommended in order to describe the actual "state of the art" of the materials after chest wall reconstructions cases and optimal therapeutic approaches. Notably, a systematic review was available only for paediatric case.

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