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Three-dimensional printed titanium chest wall reconstruction for tumor removal in the sternal region

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Abstract

Resection of thoracic wall tumors results in significant defects in the chest wall, leading to various complications. In recent years, the use of three-dimensional (3D) printed titanium alloy prostheses in clinical practice has demonstrated enhanced outcomes in chest wall reconstruction surgery. A cohort of seven patients with sternal tumors was identified for this study. Following a helical CT scan, a digital model was generated for the design of the prosthesis. Subsequently, the tumors were then removed together with the affected sternum and ribs. The chest wall was then reconstructed using 3D-printed titanium alloy prosthesis for bone reconstruction, mesh for pleural reconstruction, and flap for soft tissue reconstruction. Patients were monitored for a period of one year post-surgery. In the seven cases examined, the tumors were found in various locations with varying degrees of invasion. Based on the scope of surgical resection and the size of the defect, 3D-printed titanium alloy prosthesis was custom-designed for chest wall reconstruction. Prior to bone reconstruction, pleural reconstruction was achieved with Bard Composix E/X Mesh, while soft tissue repair involved muscle flap and musculocutaneous flap procedures. A one-year follow-up assessment revealed that the utilization of the 3D-printed titanium alloy prosthesis led to secure fixation, favorable histocompatibility, and enhanced lung function. The findings demonstrate that the utilization of 3D printed titanium alloy prostheses represents a significant advancement in the field of chest wall reconstruction and thoracic surgical procedures.

Keywords Sternal tumor, 3D printing, Titanium alloy prosthesis, Chest wall reconstruction

Introduction

Tumors originating from the tissues of the thoracic wall, including the thoracic wall bones, are known to erode both the thoracic wall and surrounding muscle tissue, causing significant damage to the structural integrity of the chest [1]. In order to remove these common thoracic tumors and the adjacent structures of the thoracic wall, thoracic surgery is often performed. However, this surgical intervention frequently leads to significant defects in the thoracic wall, resulting in abnormalities, collapse, abnormal breathing, thoracic wall necrosis, and other complications that can greatly impact the patient's quality of life [2]. Consequently, addressing such defects and

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restoring the function and integrity of the thoracic wall necessitates a comprehensive approach involving both bone reconstruction and soft tissue cover, using implants or grafts that permits the chest stabilization, are biocompatible with the body, ensures proper respiratory function, and protects the thoracic organs [3, 4].

The reconstruction process, especially in the context of skeletal repairs, is a complex and demanding task that requires careful planning and execution. Historically, various techniques have been explored and utilized for skeletal reconstruction, including the use of a mesh and methyl-methacrylate orthopedic cement prosthesis [5]. However, these materials pose challenges in terms of shaping them to precisely conform to damaged thoracic walls, as well as their tendency to move paradoxically during respiration. Therefore, these challenges impede the mending procedure and result in postoperative complications such as pain, bleeding, and limited respiratory function. To address these limitations and improve patient outcomes, it is necessary to continue researching and developing more effective and reliable skeletal reconstruction techniques.

Recently, the utilization of three-dimensional (3D) printing has become increasingly popular in the medical field. This innovative technology has found a place in various medical subdomains, particularly in the realm of surgical simulation, preoperative rehearsal, and the development of auxiliary surgical tools [6]. Its ability to produce complex structures with precise dimensions has made it a valuable tool in improving surgical outcomes. However, the concerns about the hardness, stability, and quality of 3D-printed products, which are critical for the safety and efficacy of surgical implants and prostheses, have limited the reports on the use of 3D printing technology in surgery [7]. Nevertheless, the utilization of 3D-printed titanium alloy prosthesis has addressed some of the challenges of traditional bone reconstruction techniques, and the utilization of titanium alloys in chest wall reconstruction has become prevalent owing to their exceptional attributes such as high strength, lightweight nature, and favorable tissue compatibility [7, 8].

Since 2018, our institution has been at the forefront of this innovation, implementing a titanium sternum-rib fixation system along paired with Bard Composix E/X mesh to reconstruct chest wall defects. The Bard Composix E/X mesh provides a strong and flexible scaffold that integrates seamlessly with the surrounding tissue, while the titanium sternum-rib fixation system offers a robust and stable foundation for long-term support. All chest wall defects treated with this method have been successfully reconstructed with the titanium alloy implant prostheses that are securely fixed and functioning as intended. Additionally, satisfactory histocompatibility and lung function were observed during the one-year follow-up.

Table 1 Patients information

Case	Sex	Age (years)	Tumor pathology
1	male	74	SAPHO syndrome
2	male	59	SAPHO syndrome
3	female	59	fibrosarcoma
4	male	56	fibrosarcoma
5	female	66	fibrosarcoma
6	male	32	aneurysmal bone cyst
7	male	66	carcinosarcoma

Materials and methods

Patient selection

The patients included in this study were chosen from Hebei Yanda Hospital during the period of 2018 to 2022. The criteria for selecting patients were as follows: (1) presence of a sternal tumor; (2) resection of a portion of the thoracic wall and thoracic wall muscles, resulting in postoperative defects in the thoracic wall; (3) overall good health. Patients with tuberculosis or inflammatory lesions were excluded. The clinical trial was conducted in accordance with the Helsinki Declaration and informed consent was obtained from all patients prior to surgery.

A total of seven patients were collected underwent surgery of sternal rib removal and 3D-printed titanium alloy chest wall reconstruction, comprising 5 males and 2 females, with an average age of 58.86 ± 13.30 range from 32 to 74 years old. The pathology report revealed the presence of SAPHO syndrome in 2 cases, fibrosarcoma in 3 cases, carcinosarcoma in 1 case, and aneurysmal bone cyst in 1 case. Detailed information was exhibited in Table 1.

3D-printed titanium alloy prosthesis productions

A helical CT scan was conducted using a General Electric CT scanner, and the resulting two-dimensional image slices were imported into the commercial Materialise Interactive Medical Image Control System (MIMICS) Research 20.0 (Materialise, Belgium) to prepare a digital model. Following the removal of the soft tissue, the skeleton was visualized to diagnose and evaluate the chest defect. Then, the 3D data was imported into Siemens NX10 (Siemens PLM Software, Germany) for prosthesis design. Finally, the titanium alloy prosthesis was manufactured using an Electron Beam Melting (EBM) Q10 3D printer (Arcam, Sweden).

The operation

After the administration of general anesthesia, an anterior median chest incision and free flap were performed. An arcuate expansion resection was conducted at the bone and soft tissue margins, maintaining a distance of 4 cm from the tumor margins. This resection included the predetermined sternum and ribs on both sides, as well as adjacent lymph nodes and infiltrated peripheral soft tissues. In cases where invasion of the pericardium and diaphragm occurred, resection was performed concurrently. The excised margins were then sent to the Department of Pathology for intraoperative frozen section analysis.

The reconstruction of the chest wall was conducted subsequent to surgery, wherein 3D-printed titanium alloy prosthesis was utilized for the purpose of thoracic bone reconstruction. In cases where patients underwent total sternum or sternal manubrium resection, the prosthesis was implanted utilizing a bilateral sternoclavicular joint soft link. The suprasternal muscle was sutured to the prosthesis, and the prosthetic rib and rib resection stumps were fixed with titanium rib claws. For patients who underwent middle-lower sternal tumor resection, the sternal manubrium was preserved, and the implanted prosthesis was connected to the sternal manubrium using screws. Prior to bone reconstruction, pleural reconstruction was conducted using Bard Composix E/X Mesh, while soft tissue repair utilizing musculocutaneous flaps.

Follow-up visit

The patients underwent regular follow-up examinations for duration of one year, during which assessments were made regarding wound healing, rejection reaction, prosthetic fixation and lung function after the surgery.

Results

Characteristics of tumor in cases

Among the seven cases examined, the tumors were found in various locations, including two cases in the sternal manubrium and right clavicle, one case in the sternal manubrium and sternal body, one case in the sternal body alone, and three cases in the parietal sternal body. Additionally, all seven cases exhibited sternum invasion without involvement of the thoracic vertebra invading, with five cases also showing invasion of the clavicle or rib. The size of the tumors ranged from a maximum of 10.0 cm × 8.0 cm to a minimum of 3.0 cm × 3.0 cm (Table 2).

Table 2 Characteristics of tumor in cases

Case	Tumor size (cm× cm)	Whether to invade the sternum	Whether to invade the thoracic vertebra	Whether to invade the clavicle or rib
1	3.0×3.5	yes	no	yes
2	3.0×3.0	yes	no	yes
3	3.0×3.5	yes	no	no
4	8.0×10.0	yes	no	yes
5	5.0×13.0	yes	no	yes
6	3.5×4.0	yes	no	no
7	5.0×6.0	yes	no	yes

Information of tumor resection

3D digital models of thoracic tumors and the surrounding structures were effectively generated (Fig. 1A). The 3D reconstruction model facilitated the determination of the extent of surgical resection, as well as provided comprehensive information regarding the size, area, and shape of the excised thoracic wall, thus ensuring sufficient preoperative knowledge. Within the cohort of seven patients enrolled in this study, the surgical interventions performed were as follows: one patient underwent resection of the total sternum and portions of bilateral ribs 1–7, two patients underwent resection of the sternal manubrium, 1/2 right clavicle and a portion of the first rib bilaterally, one patient underwent resection of 1/2 sternal manubrium and bilateral ribs 2–7, and two patients underwent resection of the sternal body and bilateral ribs 3–7, one patient underwent resection of 3/4 sternal body and bilateral ribs 4–7. The resection margin of both bone and soft tissue measured 4 cm from the tumor, and all intraoperative frozen margin samples yielded negative results. The range of resection, including both bone and soft tissue, varied between 88 and 196 cm^2 (Table 3). Notably, due to the close proximity of sternal manubrium and clavicle tumors to major blood vessels in two patients, a preoperative investigation utilizing 3D-visualization and virtual reality technology was undertaken to reconstruct the spatial relationships between the tumors and their adjacent blood vessels (Fig. 1B-C). This approach effectively facilitated intraoperative guidance and minimized the risk of subclavian and innominate vein damage.

Chest wall reconstruction

The prosthesis was fabricated and produced subsequent to a preoperative high-precision 3D reconstruction (Fig. 2). The design of the sternal manubrium incorporates considerations for the reconstruction of the sternoclavicular joint and the suprasternal musculature, employing a pre-drilled hole. The central portion of the sternum is composed of a metal mesh and ribs porous design, which serves to reduce the weight and facilitate to integrate surrounding tissues. This model possesses the capability to fully reconstruct the anatomical structure, while also offering customization options and reduced weight.

Then the reconstruction of the chest wall was conducted using 3D-printed titanium alloy prosthesis (Table 3). All seven patients underwent implantation of 3D-printed titanium prosthesis with a reconstructed area ranging from 153 to 288 cm^2 and the prosthesis weight ranging from 42 to 145 g. Out of the seven patients, two

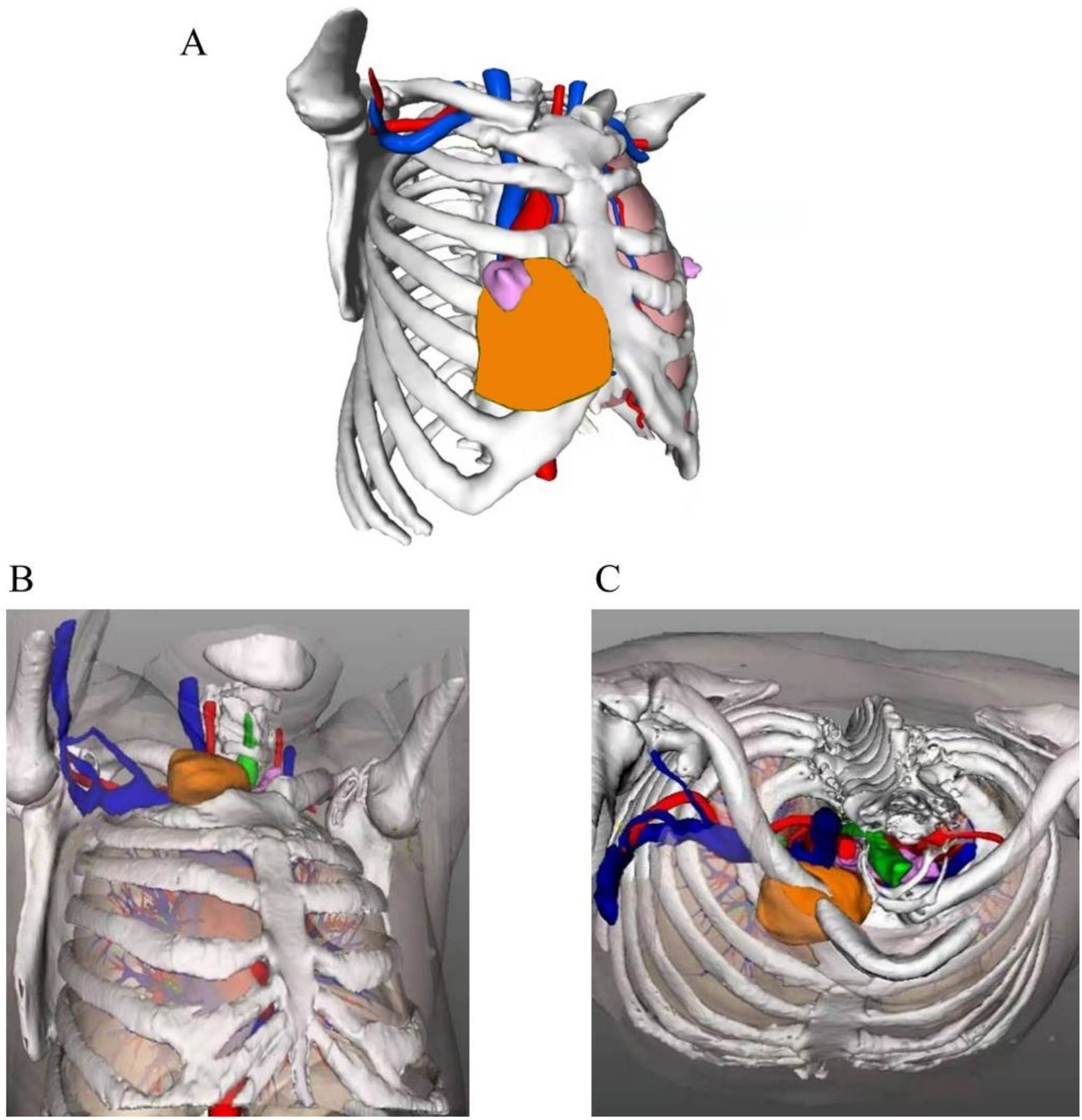

Fig. 1 3D digital models. (**A**) 3D model of thoracic tumor and the surrounding structures. (**B-C**) 3D reconstruction of tumor-vessel relationships. Red represents artery, blue represents vein, orange represents tumor, white represents bones, fuchsia represents mammary gland, pink represents lung

underwent sternal manubrium and sternal body resection with prosthesis implantation, utilizing sternoclavicular joint soft link and titanium rib claws (Fig. 3), two others had their sternal manubrium removed and replaced with a prosthesis, also using sternoclavicular joint soft link and titanium rib claws (Fig. 4). Besides, three patients underwent sternal body resection with prosthesis implantation using screw (Fig. 5). Prior to bone reconstruction, pleural reconstruction was carried out using Bard Composix E/X Mesh (Fig. 3B). Besides, soft tissue repair involved the use of muscle flap and musculocutaneous flap (Fig. 6). Specifically, pectoralis major muscle flap were used in four cases, latissimus dorsi musculocutaneous flap in two cases, and rectus abdominis musculocutaneous flap in one case.

Table 3 Information of chest wall reconstruction

Case	Scope of surgery resection	Area of defect (cm^2)	Area of implanted prosthesis (cm^2)	Weight of implanted prosthesis (g)	Chest wall reconstruction method
1	Sternal manubrium + 1/2 right clavicle + portion of first rib bilaterally	88	170	42	3D-printed titanium alloy prosthesis + Pectoralis major muscle flap
2	Sternal manubrium + 1/2 right clavicle + portion of first rib bilaterally	92	187	50	3D-printed titanium alloy prosthesis + Pectoralis major muscle flap
3	Sternal body + portion of 3rd – 7th ribs bilaterally	120	196	90	3D-printed titanium alloy prosthesis + Pectoralis major muscle flap
4	1/2 sternal manubrium + sternal body + portion of ribs 2–7 bilaterally	196	288	145	3D-printed titanium alloy prosthesis + Latissimus dorsi musculocutaneous flap
5	Sternal manubrium + sternal body + portions of ribs 1–7 bilaterally	154	240	121	3D-printed titanium alloy prosthesis + Latissimus dorsi musculocutaneous flap
6	Sternal body + portion of 3rd-7th ribs bilaterally	132	210	96	3D-printed titanium alloy prosthesis + Pectoralis major muscle flap
7	3/4 sternal body + portion of 4th-7th ribs bilaterally	98	153	81	3D-printed titanium alloy prosthesis + Rectus abdominis musculocutaneous flap

Postoperative treatment

Following surgery, the tracheal intubation is typically removed once the patient has achieved a stable condition. Subsequently, patients are transferred from the intensive care unit to the general ward within a span of 1–2 days. Two days post-surgery, patients are advised to mobilize and the postoperative analgesic pump is utilized for a period of 3–5 days. The postoperative pain experienced by the patient is comparable to that of standard surgery. One week after the operation, the patient begins to do respiratory rehabilitation training. It is imperative that the postoperative chest strap is securely fastened for a duration of 3 months. Additionally, patients are advised to abstain from high-temperature hot baths and saunas.

Prognosis and follow-up

Among the seven cases examined, six exhibited successful wound healing within a single stage after surgery, while one case experienced delayed healing. Notably, the titanium alloy implant prosthesis demonstrated secure fixation at the one-year follow-up. Additionally, the observed wound healing and histocompatibility were considered satisfactory, as no instances of rejection reaction were detected during the six-month postoperative observation period. Lung function has also improved.

Discussions

In recent years, notable advancements have been made in the application of 3D printing technology in thoracic surgery [9]. This advancement is crucial, particularly in the context of addressing sternal defects resulting from the resection of sternal tumors. 3D-printed titanium alloy prosthesis can be personalized according to the patient's own characteristics, it becomes feasible to accurately replicate the patient's individual anatomical structure [10]. This approach effectively resolves the issue of sternum and rib defects, ensuring chest wall integrity and stability, which plays a pivotal role for protecting organs in the thoracic cavity and mediastinum, as well as maintaining normal respiratory function. Before the introduction of 3D printing technology in clinical practice, the reconstruction of patients with chest wall defects was traditionally carried out using materials such as metal mesh, rib plates, and plexiglass. However, these materials lacked the necessary robustness, stability, and durability required for a successful thoracic reconstruction. The titanium alloy prosthesis implant emulates bone trabeculae's microporous structure, promoting the growth of human bones and soft tissues. Moreover, titanium possesses similar hardness and elasticity to bones and can integrate efficiently with human tissues. Furthermore, titanium prostheses have demonstrated exceptional resistance to corrosion, enhanced stability, and superior firmness. These properties make them highly suitable for use

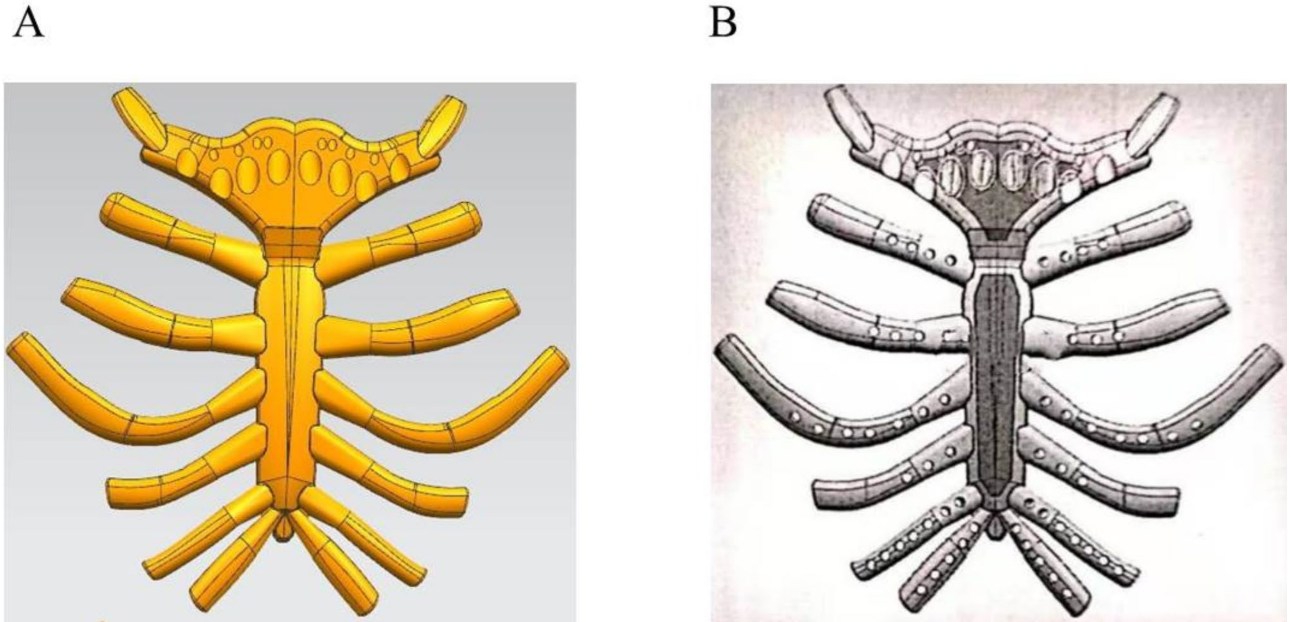

Fig. 2 Design of the prosthesis. (**A**) Sternal manubrium was conducted with pre-drilled holes for the reconstruction of the sternoclavicular joint and the suprasternal musculature. (**B**) 3D-printed titanium alloy prosthesis. The central portion of the sternum is composed of a metal mesh and ribs with a porous design

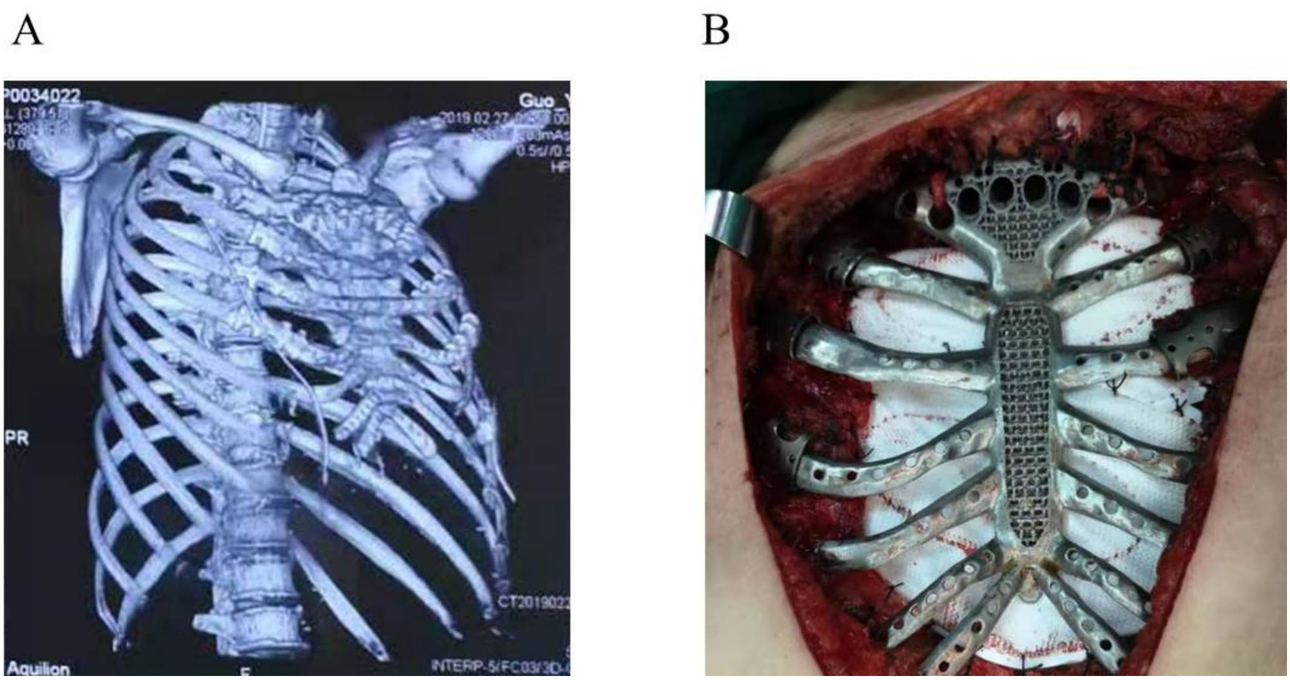

Fig. 3 View of prosthesis implanted with total sternum resection. (**A**) Chest computed tomography scan 3D reconstruction of titanium alloy prosthesis showing total sternum and bilateral ribs. (**B**) Intraoperative image showing sternoclavicular joint, suprasternal muscles and rib links

in the construction of artificial hip joints, dental roots, bone plates, and screws, thereby presenting an effective solution for the management of sternum and rib defects [11, 12].

Regarding the extent of tumor resection, it is advised that the margins of the sternum and bilateral ribs should exceed a distance of 4 cm in distance from the tumor, since intraoperative frozen pathology biopsy on bone tissue is not feasible. Additionally, for soft tissue margins, if the tumor infiltrates the muscle and skin, it is imperative to exceed an excision distance of 4 cm from the tumor and undertaken an excision of affected muscle and skin

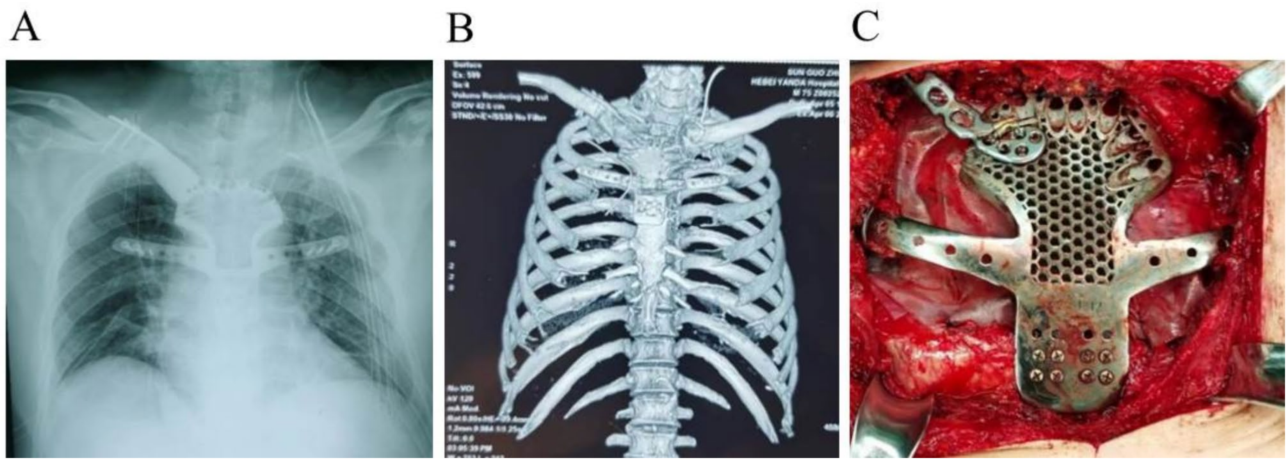

Fig. 4 View of prosthesis implanted with sternal manubrium resection. Chest X-ray (**A**) and computed tomography scan 3D reconstruction (**B**) of titanium alloy prosthesis showing sternum manubrium and clavicle. (**C**) Intraoperative image showing the link of the prosthesis and sternal body with screws

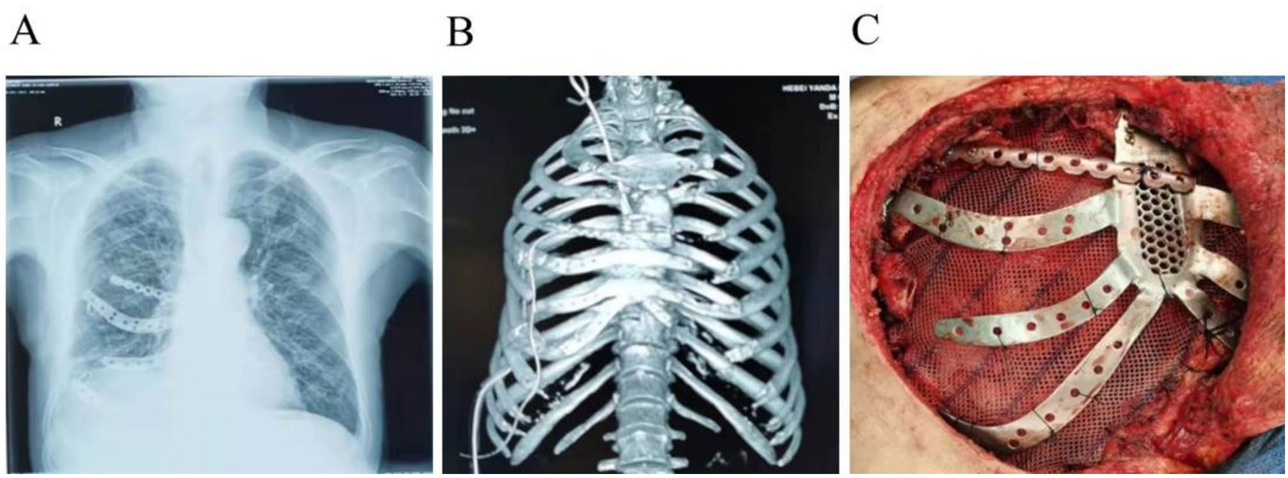

Fig. 5 View of prosthesis implanted with sternal body resection. Chest X-ray (**A**) and computed tomography scan 3D reconstruction (**B**) of titanium alloy prosthesis showing sternum body and clavicle. (**C**) Intraoperative image showing the link of the prosthesis and sternal manubrium with screws

resection [13]. The majority of studies have demonstrated that expanding the extent of resection is correlated with a reduction in the occurrence of local recurrence rate after surgery. As a result, the extent of resection performed on the tumor plays a crucial role on the survival of patients [14, 15]. In our surgical approach, we conducted an arcuate expansion resection at the bone and soft tissue margins, maintaining a 4 cm distance from the tumor margins. This method exhibited favorable outcomes.

Since extensive resection has been shown to improve the five-year survival rate, albeit at the expense of generating a larger chest wall defect in comparison to palliative resection, reconstructing such a substantial defect using conventional materials becomes challenging. However, the utilization of 3D-printed titanium prosthesis has emerged as a feasible solution for thoracic reconstruction [16]. The emergence of 3D-printed sternum and rib implants represents a recent advancement in chest wall reconstruction, enabling personalized and precise reconstruction in clinical contexts. In the design of the 3D implant prosthesis, many key factors need to be considered. Firstly, high-precision 3D CT scanning is utilized to acquire thoracic images prior to surgery. There images are then used to determine the extent of resection and the appropriate size and dimensions for implanting a titanium alloy prosthesis. Secondly, the design of the sternal manubrium considers the reconstruction of the sternoclavicular joint and the suprasternal musculature, resulting in the creation of a pre-drilled hole. The sternum's central region is constructed from a metallic mesh, while the ribs feature a porous pattern. These design elements serve to decrease the weight of the titanium alloy prosthesis, facilitate the integration of surrounding tissues, and promote implant stability. Thirdly, each rib of the prosthesis extends 2.5–3 cm beyond the predicted resection margin, ensuring ample length for rib linkage. The

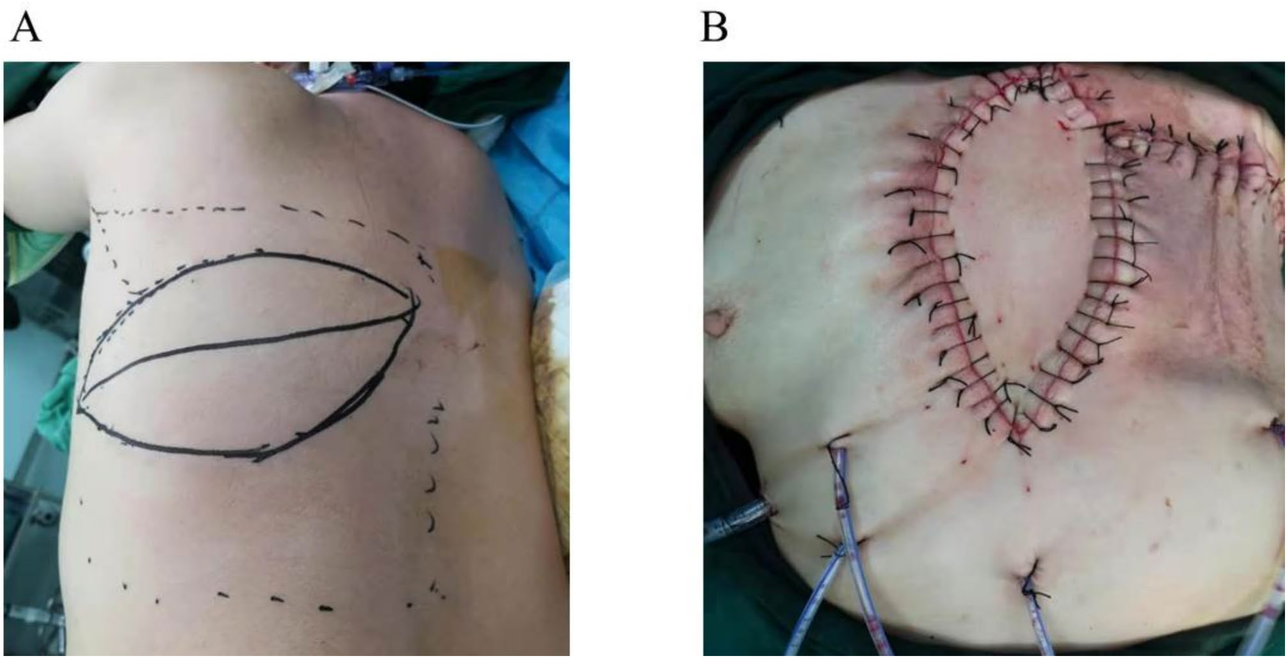

Fig. 6 Soft tissue repair of musculocutaneous flap. (**A**) Musculocutaneous flap utilized for soft tissue reconstruction was derived from the patient's own Latissimus dorsi. (**B**) The Latissimus dorsi musculocutaneous flap was transferred to the chest wall to address the chest defect

sternal body was resected with strategically placed holes for connecting the holes with the sternal manubrium. Moreover, the properties of titanium alloy materials can be influenced by a multitude of physical and chemical factors. These considerations must be taken into account during the design and installation process of implants. For instance, the design of the implant material should exceed the dimensions of the chest wall defect. Additionally, the connection between the implanted 3D printed material and the sternum and ribs should be designed to avoid excessive tightness [17].

The patient's thin-layer chest CT data was collected before the operation to design of the prosthesis. The prosthesis implant was then manufactured in one-to-one ratio with the patient's sternum and ribs. Before printing the titanium alloy prosthesis, simulation model printing and human body proofreading were conducted to thoroughly evaluate the extent of lesion resection, as well as to precisely adjust the size and dimension of the titanium alloy prosthesis. Given the inability to modify the shape or size of 3D-printed implants during surgery, it is imperative to anticipate and prevent any potential issues. To circumvent the issue of a 3D printed implant being undersized due to an underestimated tumor size, it is crucial to accurately delineate the resection scope prior to surgery. If the tumor scope and boundary are not clearly discernible from a CT scan, a PET-CT scan can be employed for further clarification. However, even with these measures, there may be instances where the surgical margin of the tumor is larger than anticipated and does not align with the printed prosthesis. In such cases, alternative solutions may be required, such as the approach illustrated in Fig. 5, which involves an expanded resection and the use of a spare rib plate to bridge and repair the rib defect. To prevent displacement and fracture of the connection, we employed entangled titanium alloy rib claw or screw fixation. If the screws are loose due to osteoporosis of the sternum, wire ties can be used for additional reinforcement. Intraoperative and postoperative assessment of chest CT scans confirmed the secure and stable fixation of the titanium prosthesis to the ribs, resulting in good surgical outcome was good. The consideration of the connection between the rib stump and the implanted prosthesis necessitates the examination of factors such as the the modulus of titanium prosthesis and rib, as well as the difference in biomechanical properties between the implant and cortical bone. The titanium alloy material, titanium alloy rib claw and screw we selected exhibit enhanced biocompatibility, rendering it more prone to osseointegration with bone tissue and consequently resulting in a stronger histological connection [18, 19].

The process of reconstruction necessitates the stabilization of the chest wall and the restoration of soft tissues [20]. In addition to bone restoration for chest wall stabilization, soft tissue reconstruction, encompassing pleural reconstruction and muscle and skin flap reconstruction, is essential for maintaining thoracic stability and morphology. Pleural reconstruction effectively maintains pleural cavity stability, enables the adhesion of the visceral pleura of the lung surface to the artificial pleura, reduces the occurrence of effusion and pneumoperitoneum, and promotes the adhesion of the surrounding soft tissues [21, 22]. The study subjects received Bard Composix E/X Mesh as the material for pleural reconstruction, yielding positive results. Due to the extensive resection of the sternum and rib tumor and the impact of bilateral internal mammary artery ligation on the blood supply to the rectus abdominis muscle, the initial consideration for soft tissue defect reconstruction involved the use of either a latissimus dorsi muscle flap or musculocutaneous flap transplantation. To avoid compromising the blood supply to the grafted muscle flap, routine chest CT enhancement was performed to prevent ischemia of the dorsal thoracic artery and aid in the reconstruction process. If resection of the sternal manubrium, first rib, and sternoclavicular joint is required, connecting apertures are installed in the prosthetic sternal manubrium to facilitate the soft tissue attachment. In a patient of total sternotomy, the soft connection of the sternoclavicular joint and the suprasternal muscle enabled 3D reconstruction of the sternoclavicular joint, resulting in the restoration of the anatomical and physiological function.

In the forecast, the utilization of 3D-printed titanium alloy prosthesis exhibited dependable fixation, satisfactory histocompatibility, and good pulmonary function. Hence, the use of 3D printing techniques proved successful in facilitating the resection of sternal tumors and chest wall reconstruction. These outcomes signify a significant advancement in chest wall reconstruction and thoracic surgical techniques. As we continue to gather data and refine our techniques, we are optimistic that this approach will become a standard of care. It will offer patients a safer, more effective, and more comfortable road to recovery.

Author contributions

Wenzhang Wang: Conceptualization, Methodology, Investigation, Data collection and analysis, Validation, Writing-Original Draft Preparation. Shiyan Yang, Menghu Han, Haifeng Liu, Qing Feng: Methodology, Data collection. Yonglin Su: Data collection and analysis. Yi Han: Methodology, Data curation, Validation. Jin Wang: Conceptualization, Methodology, Validation, Data Curation, Writing-Original Draft Preparation, Writing-review & editing. All authors reviewed the manuscript.

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Data availability

Data is provided within the manuscript information files.

Declarations

Competing interests

The authors declare no competing interests.

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