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Sternal Reconstruction Using 3D-Printed Titanium Custom-Made Prosthesis for Sternal Dehiscence After Cardiac Surgery

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ABSTRACT

Sternal dehiscence is an important complication that increases mortality and morbidity in cardiac surgery. Titanium plates have been used to reconstruct the chest wall for a long time. However, with the rise of 3D printing technology, a more sophisticated method, is making a breakthrough. Custom-made 3D-printed titanium prostheses are increasingly used in chest wall reconstruction because they allow almost perfect fitting to the patient's chest wall and lead to good functional and cosmetic results. This report presents a complex anterior chest wall reconstruction using a custom-made titanium 3D-printed implant in a patient with a sternal dehiscence after coronary artery bypass surgery. At first, reconstruction of the sternum was performed using conventional methods, which failed to give adequate results. Finally, a 3D-printed titanium custom-made prosthesis was used for the first time in our center. On the short- and mid-term follow up, good functional results were achieved. In conclusion, this method is suitable for sternal reconstruction after complications in the healing process of median sternotomy wounds in cardiac surgery, especially where other methods do not provide satisfactory results.

INTRODUCTION

Even though minimally-invasive and sternum-sparing approaches increasingly are used in everyday practice, median sternotomy still is the standard incision used in cardiac surgery [Sargent 1991]. Sternal dehiscence is a challenging complication that occurs in 0.3–5% of cases [Voss 2018] and is associated with significantly higher postoperative mortality, morbidity and cost [Voss 2018; Heilmann 2013; Kaul 2017; Listewnik 2019]. Some predisposing factors for impaired sternal healing include concomitant diseases, such as chronic obstructive pulmonary disease (COPD), diabetes, obesity, infection, or bilateral internal mammary artery harvest [Sargent 1991; Kaul 2017]. Although in most cases sternal dehiscence can be managed with rewiring, this method often fails in cases of multiple sternum fractures or re-dos [Voss 2018]. Other options include a variety of muscular flaps (pectoralis, latissimus, rectus) [Kaul 2017], allogenic bone grafts [Kaul 2017; Dzian 2018], or the use of moldable titanium plates, bars, and meshes [Aranda 2015]. With the rise of 3D printing and its use in medicine, there is an increasing number of reports on 3D-printed titanium plates for chest wall reconstruction.

However, the vast majority of reported cases are primary reconstructions after chest wall tumor resections. There has been very little experience with this method in complicated sternal dehiscence and destruction after cardiac surgery. In this report, we present a complex anterior chest wall reconstruction using a custom-made titanium 3D-printed implant in an asthmatic patient with a sternal dehiscence after coronary artery bypass surgery who was additionally postoperatively infected with COVID-19.

CASE REPORT

A 77-year-old male patient with a severe symptomatic three-vessel coronary artery disease not suitable for a percutaneous intervention was scheduled for coronary artery bypass grafting (CABG). Regarding comorbidities, he suffered from severe asthma and was on combined therapy. Although he was under regular follow up with a pulmonologist, he repeatedly suffered from severe cough. A standard sternotomy was performed with left internal thoracic artery (LITA) harvesting using skeletonization technique. The revascularization procedure was performed using cardiopulmonary bypass. During surgery, the LITA was used for a bypass to the left anterior descending artery (LAD). In addition, two venous bypasses were made to bypass the stenoses on the right coronary and obtuse marginal artery. The sternotomy was closed with five figure-of-eight sternal steel wires. Soft tissues were closed in layers in a usual manner.

In the postoperative period, the patient suffered from pneumonia with bilateral pleural effusion and worsening of asthma symptoms, including severe cough. In order to prevent sternal complications, a QualiBreath sternal support

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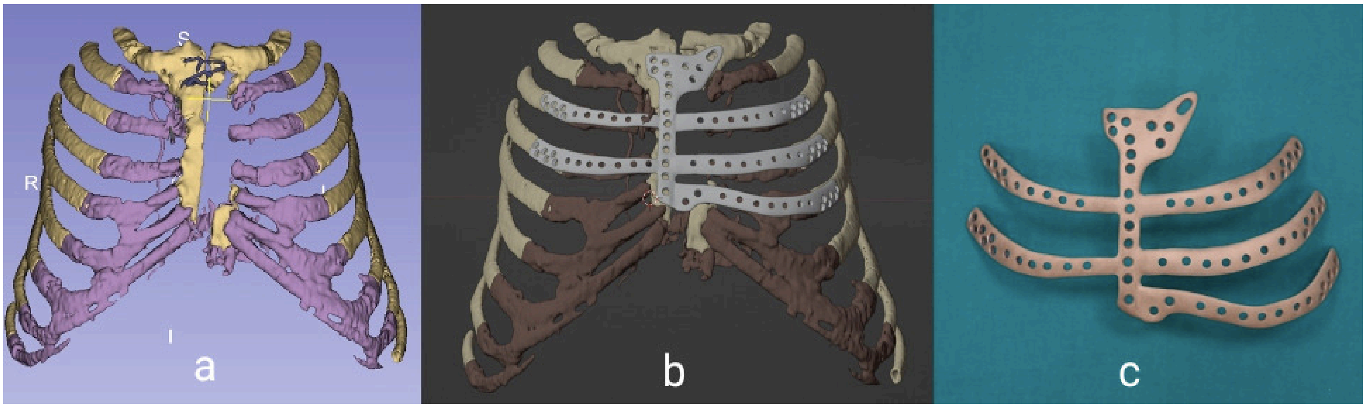

Figure 1. Stages of customized implant production. A) Reconstruction of the chest wall skeleton with 3D Slicer (https://www.slicer.org); B) The final 3D model of the implant; C) The finished implant

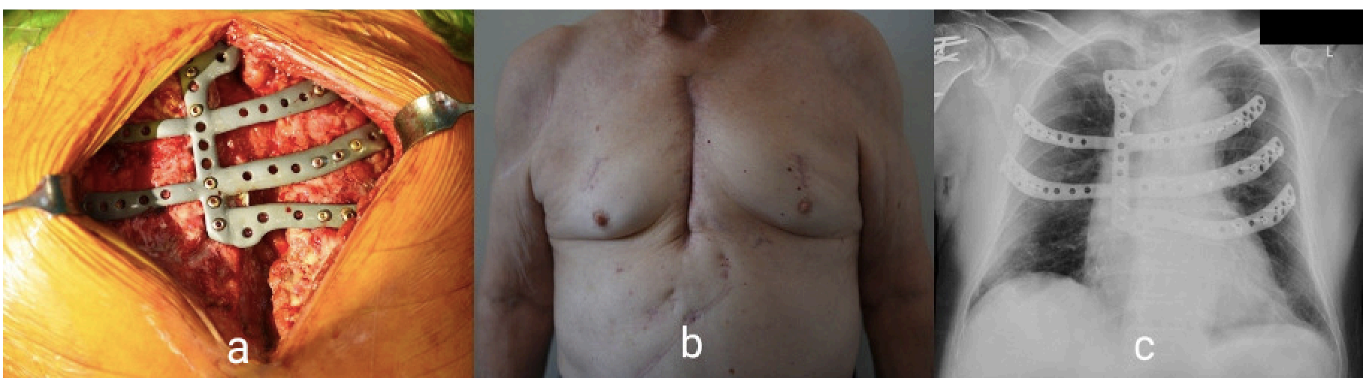

Figure 2. Implantation of the prosthesis and results. A) Intraoperative view; B) Final cosmetic result of the wound; C) Follow-up chest x-ray

brace (QualiTeam, Chiaverano, Torino, Italy) was implemented. Despite aggressive therapeutic and preventive measures, an instability of the sternum was observed on day 10 postoperatively. The sternotomy wound was opened, and a complete dehiscence of the sternum was encountered. The sternal wires cut through the bone and as a result, the sternum had two horizontal fractures on the left side and one on the right side. The wound, however, did not look infected. A swab for cultures was obtained, and the sternum was rewired using a combination of standard sternal wires and nitinol thermoactive sternal clips (Flexigrip clips, Praesidia srl., Bologna, Italy). Soft tissues were not closed then, and the negative pressure wound therapy (NPWT) system was put in place to stabilize the sternum further. The sternal support brace was continued. However, the patient continued to heavily cough and in three days, at the next change of the NPWT dressing, a complete avulsion of rib cartilages II-VII from the left side of the sternum was discovered. As a result, the left half of the sternum was totally sequestered and therefore was removed. At this point, reconstructing the chest wall with conventional methods using sternal wires or nitinol clips was impossible.

Over the next two weeks, NPWT dressings regularly were changed every 3 to 4 days, and the patient received antibiotic and anti-asthmatic treatment, supportive respiratory, and locomotor physiotherapy. In this period, the patient was fully ambulatory.

Construction of the prosthesis: A reconstruction of the sternum was discussed with engineers from the Additive Manufacturing Laboratory at the Faculty of Mechanical Engineering, University of Maribor. Based on their previous experience in the field of 3D-printed implants and medical accessories, a decision was made to construct and produce a customized titanium-aluminum-vanadium (TiAlV) alloy implant using selective laser melting technology. The implant's shape construction was based on patient's CT study data. The first step was to perform a virtual 3D reconstruction of the skeleton of the damaged sternum and surrounding structures. In this phase, it was crucial that the exact border between cartilage and bone tissue was determined. This was necessary to determine the implant's required size and to correctly predict the fixation point in cortical bone areas. This step was completed with all members of the implant planning team (surgeon, radiologist, engineer), confirming the correctness of reconstructed skeletal model.

The reconstruction was performed using a 3D Slicer (https://www.slicer.org), a free, open-source software package widely used in medical, biomedical, and related imaging research (Figure1A). (Figure 1) Afterward, separate 3D computer models of cartilage and bone structure (in STL format) were exported to Blender software, another free and open-source software (among other purposes) for modifier-based mesh modelling (https://www.blender.org). Blender was used to construct a digital model of a sternal implant. The whole implant planning team was involved.

First, a rough implant layout was created by engineers. Then, the final shape was adjusted, according to surgeon recommendations. Finally, the location of fixation holes was determined, and the shape of the holes adjusted for screws that were used at the surgery (Figure 1B). The final 3D computer model of the implant was additively manufactured (3D printed from a grade 23 titanium alloy (EOS Titanium Ti64 Grade 23, EOS GmbH Electro Optical Systems, Germany) using selective laser melting technology (EOSINT M290 machine, EOS GmbH Electro Optical Systems, Germany). The finished part weighs 53.5 g and has an overall size of 170 × 60 × 105 mm (Figure 1C). The final production step was 3D optical scanning of the implant to verify the required manufacturing accuracy. The entire process, from the first decision to delivering the finished implant to the hospital, took 15 days.

Surgical reconstruction: The approach was through the original median sternotomy wound. The area above the second to the fifth rib was dissected on both sides at least 15 cm laterally from the sternum, and the pectoral muscle was lifted. Two additional incisions were made bilaterally in the medial clavicular line, allowing the fixation of lateral parts of the prosthesis using 3.5 mm titanium screws. The prosthesis was fixated medially on the remains of the sternum and laterally to the third and fourth rib on the right side and the third to fifth rib on the left side (Figure 2A). (Figure 2)

The implant was covered with the pectoralis muscles that were medially sutured using interrupted resorbable 3-0 stitches. A redon drainage was placed under the pectoralis muscle on both sides; laterally and medially. Subcutaneous tissue and skin were closed in a usual manner. Postoperative course was surgically uneventful with good tissue healing.

During the post-reconstruction period, the patient tested positive for COVID-19 on day 5 postoperatively. He was mildly symptomatic with some worsening of cough, but without any need for oxygen supplementation. The further postoperative course was uneventful with good functional and cosmetic results. The patient eventually was discharged from the hospital 52 days after CABG and 16 days after the final sternal reconstruction.

During follow up, there were no complications of the surgical wounds (Figure 2B), there was no instability of the chest wall, and the patient's only complaint was occasional mild pain in the medio-clavicular lines on both sides. A control chest x-ray was performed, which did not show dislocation of the implant or any other potential pathology (Figure 2C). At 1-year follow up, the patient is doing well and is able to do physical activities, such as hiking, without any problems.

DISCUSSION

Sternal dehiscence is a major complication leading to increased mortality and morbidity in cardiac surgery [Sargent 1991]. There are numerous qualities sought in materials used in the sternal reconstruction. The main goals to strive for are maintenance of the shape of the chest wall, not over-burdening the ribs with the prosthesis, and prevention of paradoxical breathing patterns. The ability of a material to allow fibrous tissue ingrowth and decrease the likelihood of infection also is important. In terms of practicality, the material should be mendable to be shaped in a suitable form, during the operation. Another important quality also is radiolucency, which allows the possibility of further diagnostics and evaluation of the tissues behind the prosthesis. Additionally, the implanted material ideally should allow easy and fast access to the mediastinum in case of an emergency [Wen 2018; Wang 2019; Goldsmith 2020].

Among the most common methods of sternal reconstruction used in cardiac surgery are still pectoralis, rectus, latissimus flaps, and omental grafts [Kaul 2017]. Allogeneic bone transfers also are used, with significant limitations of donor bone availability, difficulty in 3D contouring, poor tissue tolerance and acceptance, and risk of long-term pain syndrome or discomfort [Wen 2018]. However, muscular flaps most often result in additional surgical trauma with its own risk of inadequate wound healing and infection.

There is a wide array of alloplastic materials used in reconstruction. Synthetic meshes (such as Gore-Tex soft tissue patches, Prolene mesh patches, as Marlex® mesh) are prone to propagate tissue growth, but their main downside is the lack of strength and rigidity [Dzian 2018; Goldsmith 2020; Wang 2020]. Bone substitutes and sandwiches with mesh and methyl methacrylate provide more rigidity, and the latter also is radiolucent. Osteosynthesis systems and dedicated plastic or metallic prostheses (stainless steel net, titanium mesh, titanium plate, or plexiglass) tend to provide good chest wall rigidity. However, the main problem is their inelasticity and general pre-manufactured shape, often making it harder to restore the original shape of the chest wall in more extensive defects [Dzian 2018; Wen 2018; Wang 2019; Goldsmith 2020; Wang 2020].

Although titanium plates and implants are an adopted technique for sternal reconstruction [Wen 2018], with the rise of 3D printing and its use in medicine, there have been several promising reports on the use of 3D-printed customized titanium prostheses [Dzian 2018; Aranda 2015; Wen 2018; Goldsmith 2020; Wang 2020]. Even though most of them have been used in the defects on the chest wall caused by tumor resection, in our case report, we show that this method successfully can be implemented in complications after median sternotomy in cardiac surgery. 3D printing offers a personalized approach to the reconstruction of the sternum. As the prosthesis is made according to a CT scan of the patient's chest wall, the shape fits perfectly, and there is no need to cut, mold, or shape the prosthesis in any way in the operating room [Aranda 2015].

As Aranda [Aranda 2015] has noted, the 3D-printed titanium prosthesis is suitable for patients with extensive sternal defects, especially for patients in whom simpler techniques do not provide satisfying results.

To conclude, 3D-printed custom-made titanium prosthesis appears to be a promising solution for sternal reconstruction in cases of post-sternotomy complications in cardiac surgery, especially when other methods fail to deliver acceptable results. In our case report, we observed excellent functional and cosmetic results. The main drawback, however, is an anticipated difficult and time-consuming removal of the prosthesis in case of a need for an emergent approach to the mediastinum. Although we are providing some insight into mid-term results, more cases and a longer follow up will be required to better evaluate and assess the method.

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