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Three-Dimensional Printing for Chest Wall Reconstruction in Thoracic Surgery: Building on Experience

Jeremy Smelt[1]   Antonia Pontiki[2]   Marjan Jahangiri[3]   Kawal Rhode[2]   Arjun Nair[1]   Andrea Bille[1]

[1] Department of Thoracic Surgery, Guy's and Saint Thomas' NHS Foundation Trust, London, London, United Kingdom of Great Britain and Northern Ireland
[2] King's College London School of Medical Education, London, London, United Kingdom of Great Britain and Northern Ireland
[3] Department of Cardiothoracic Surgery, St George's Hospital, London, United Kingdom of Great Britain and Northern Ireland

Address for correspondence Jeremy Smelt, FRCS (CTh), Department of Thoracic Surgery, Guy's and Saint Thomas' NHS Foundation Trust, London, London SE1 7EH, United Kingdom of Great Britain and Northern Ireland (e-mail: jeremysmelt@doctors.org.uk).

Abstract

Objectives   Patients undergoing surgery for locally advanced lung cancer involving the chest wall require anatomical lung with extensive en-bloc chest wall resection and appropriate reconstruction.

In this proof-of-concept study, we aimed to produce personalized three-dimensional (3D)-printed chest wall prosthesis for a patient undergoing chest wall resection and reconstruction using clinically obtained computed tomography (CT) data.

Methods   Preoperative CT scans of three patients undergoing chest wall resection were analyzed and the areas of resection segmented. This was then used to produce a 3D print of the chest wall and a silicone mold was created from the model. This mold was sterilized and used to produce methyl methacrylate prostheses which were then implanted into the patients.

Results   Three patients had their chest wall reconstructed using this technique to produce a patient specific prosthesis. There were no early complications or deaths.

Conclusions   It is possible to use 3D printing to produce a patient specific chest wall reconstruction for patients undergoing chest wall resection for malignancy that is cost-effective. This chest wall is thought to provide stability in the form of prosthetic ribs as well compliance in the form of an expanded polytetrafluoroethylene patch. Further research is required to measure chest wall compliance during the respiratory cycle and long-term follow-up from this method.

Keywords
► 3D printing
► chest wall
► thoracic surgery
► prosthesis
► lung cancer

Introduction

Three-dimensional (3D) printing was developed by Chuck Hull and was initially reported in the early 1980s.[1] The concept involved the production of objects by printing in layers using a variety of materials.[2] 3D printing is used throughout industry to produce objects using rapid prototyping machines and require data input in the form of machine-readable files.[3]

Medicine has started to utilize 3D printing in various ways from planning operation by printing structure to simulating surgeries by operating on these models.[4,5] In cardiothoracic surgery, the uptake has been even more limited with only a few case reports in the literature and no established practice involving 3D printing described. 3D printing has been shown to be successful in the production of medical prosthesis.[6] Previously, this has been a financial and time costly process of ordering made to fit prosthetics which have to be designed and drawn using scans and then produced or using off the shelve type prosthetics that have to be tailored intraoperatively to fit a specific patient's anatomical requirements.

3D printed prosthetics can now be delivered within hours using radiological images of the patient.[7] This has been particularly beneficial in orthopedic, maxillofacial, and cranial surgery.[8]

Developments in health care, and especially thoracic surgery, as well as multimodality treatment for locally advanced cancer, have increased the number of patients undergoing lung resections.[9] Not only are patients being diagnosed earlier due to improved access to medical care and better radiological assessment but also surgeons are expanding their case load to include patients that were previously seen as inoperable.[10–14] Now with a multimodality approach and these new available techniques, locally advanced cancer involving the chest wall can be resected completely with satisfactory reconstruction. The mortality risk of lung resections that include a chest wall excision is quoted as being three times more than an equivalent lung resection alone and account for 5% of all lung tumors.[15] This is probably due to the impact of respiratory mechanics after an extensive chest wall resection. En-bloc resection of lung tumors invading the chest wall is required to provide clear resection margins and to improve patient prognosis.[12,13,16] Chest wall resections will therefore require new reconstruction techniques to improve outcome and reduced mortality.

Chest wall reconstruction is required to provide both external protection to visceral structures and compliance during the physical action of respiration and cough mechanism. Historically, methyl methacrylate cement has been used to fill the defect, often between two layers of mesh; however, this results in poor respiratory compliance of the bony thorax as the "sandwich" is rigid.[17,18] Using more compliant material can result in paradoxical chest wall movement due to the normal intrathoracic pressure changes during respiration.[19]

Our aim has been to create personalized prosthesis for chest wall reconstruction that (1) is implantable with usual surgical techniques; (2) replicates physiological compliance, and anatomical structure and protection; (3) is cosmetically and aesthetically acceptable; and (4) is cost-effective. In this study, we report the outcomes of three patients who underwent chest wall reconstruction using the preoperative thoracic computed tomography (CT), acquired as part of a patient's standard presurgical workup, and 3D printing to develop custom-made ribs that were implanted in the patients.

Materials and Methods

Approval for the study from the joint research and enterprise office was obtained and the requirement for consent was waived. The clinical governance committee approved the procedure as this is a modification of a technique using material that is commonly used.

Two patients undergoing thoracotomy and right upper lobectomy with chest wall resection for non-small cell lung cancer were included in the series. They were both male with ages of 64 and 65 years of age and performance statuses of 0 to 1. Both patients were ex-smokers. The pathological stages were T4N0M0 adenocarcinoma and T4N1M0 squamous cell carcinoma, respectively. Four ribs were excised in the first

patient and three in the second patient. A third patient had a sternal reconstruction after resection for localized recurrence of breast cancer. This patient was female and 63 years of age.

All three patients had their chest wall segmented from a preoperative CT scan and sternal or rib molds were produced using 3D printing. These molds were then used to create custom-made prostheses that were implanted into the patient following chest wall resection.

Post-Processing of CT Images

CT scanning was performed at 100 to 120 kV and 80 to 229 mA tube current (varying according to patient weight), with helical acquisition, the patient supine, and a total scanning time of 50 seconds. All scans were acquired after a delay of ~30 seconds following intravenous administration of a 100 mL bolus of iodinated contrast (Omnipaque 300). The acquired contrast-enhanced CT images were of 2.00 mm reconstructed slice thicknesses, using standard (STD—low frequency) and bone (high frequency) kernels and anonymized. The patient's preoperative CT was acquired through a series of images in Digital Imaging and Communications in Medicine format which were uploaded to the segmentation software, ITK-Snap 3.6.0.[20] The relevant ribs or sternum were segmented (►**Fig. 1**).

Modeling and 3D Printing of the Rib/Sternal Shape

This data was then processed with the software MeshLab (MeshLab 2016, Pisa, Italy)[21] to manipulate the surface mesh of the model prior to converting the data into a solid structure using Solidworks (Solidworks Student Edition 2016–2017, Dassault Systèmes, France). Cura (Ultimaker Cura 3.2, the Netherlands) was then used to produce data that the 3D printer could use. The printer used was a WASP Delta Turbo 2040 (WASP, Ravenna, Italy), which printed the models using a filament of polylactic acid (PolyPlusTM PLA by Polymaker). The printing of the ribs or sternum was completed in around 9 hours.

Creation of the Silicone Mold

The silicone used to create the molds was the Ecoflex 00–30 (Smooth-on, Macungie, Pennsylvania, United States), which is a platinum-catalyzed soft silicone rubber. The printed ribs or sternum were placed into a cardboard box, of dimensions 8 × 18× 15cm, with their concave side down toward the bottom of the box. The silicone was poured over them up to the point where the models were completely covered. The silicone took ~24 hours to set at room temperature. Once it had completely solidified, the walls of the box were cut, and the silicone block was removed from the box. Using a utility knife, the excess silicone was cut off from the block exposing the outer side of the ribs. The models were then carefully removed taking care not to damage the silicone mold created (►**Fig. 2**).

Creation of Implants Using a Silicone Mold and Implantation

The silicone mold was sterilized and, in the operating room under sterile conditions, methyl methacrylate was mixed into a paste and applied to the silicone cast (►**Fig. 3**). After
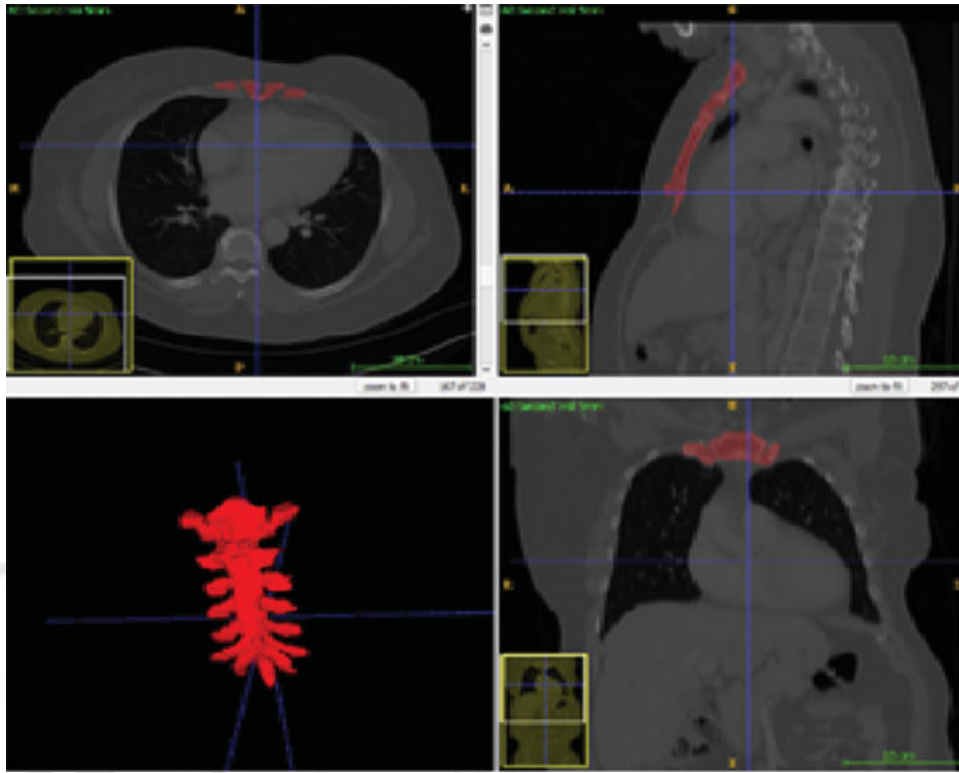
Fig. 1 The sternum having been segmented from the computed tomography scan.

Fig. 2 The mold of the sternum for a patient.

10 minutes, and once the methacrylate had set, the ribs were removed from the cast.

The methyl methacrylate chest wall prostheses were implanted into the chest wall defects (►**Fig. 4**) using heavy Prolene sutures by drilling suture holes through them (►**Fig. 5**).

Results

Three patients underwent chest wall resection and subsequent reconstruction using the described technique. The

Fig. 3 The mold of a rib mold being filled with cement.

length of stay for these patients ranged from 4 to 6 days. There were no early complications or 30-day mortality in this small cohort of patients.

The extra cost of constructing the sternum or ribs for each patient included the silicone at £31.09 and the rib or sternum printing material costing £2.90 amounting to £33.99 in total (~$44). This is more cost-effective compared with tailor made titanium prosthesis, titanium system, or cadaveric graft, which have significant higher costs.

Discussion

Although methyl methacrylate has been shown to be safe and is a common method for reconstructing the chest wall,

Fig. 4 The chest wall defect of a patient.

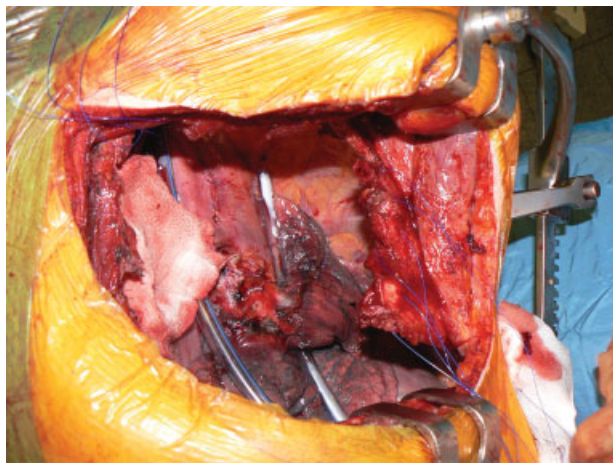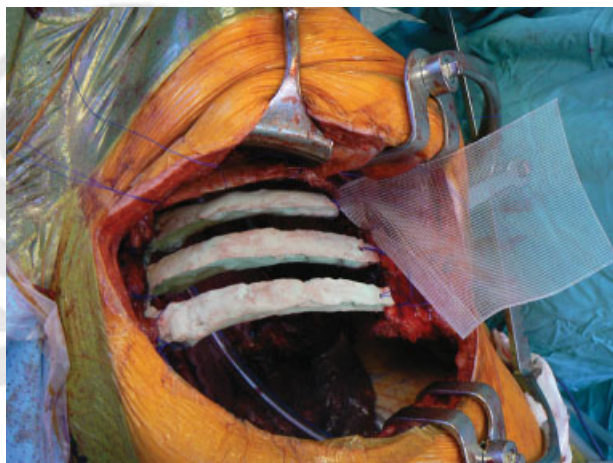**Fig. 5** The custom-made ribs having been implanted.

compliance is thought to be an issue with such a rigid structure. Solitary meshes, although compliant, lack the rigidity required to prevent paradoxical chest wall movement and protect from trauma. Some papers[23] have reported the use of "neo ribs" to provide a reconstruction that accomplishes the four ideal requirements of a chest wall prosthesis.[22–24] The concept this study has developed supports these methods with the additional use of 3D printing to improve the anatomical accuracy of the chest wall prosthesis.

As previously demonstrated by other surgeons, this technique improves cosmetics. As in the other series, we did not experience any fracture of the prosthesis or any infection. No patients experienced chronic pain or limitations to their activities of daily living.

Two drawbacks to this technique include the additional cost of using this technology, as well as the extra time involved. The cost of 3D printing is often seen as the limiting factor to this technology; however, the cost burden is the printer itself. The cost of the finished silicone mold was £33.99 (~$44) and therefore felt to be cost-effective in the setting of major chest wall surgery.

Once familiar with the software, segmentation could be successfully completed within a day by a single person and a further day was required to print the ribs. Twenty-four to twenty-eight hours were required to the produce the silicon mold and allow this to set. Sterilization took 30 minutes. The time, therefore, required to produce a sterile rib mold is also not prohibitive and can easily be achieved prior to a patient's elective surgery. The process does, however, require someone who is familiar with the process and it is relatively labor intensive during this time. While in the operating room a further 15 minutes were required to create the methyl methacrylate cement ribs from the silicon mold in a trial run. This is thought to be quicker than with the traditional methods as intraoperative measurements when producing a prosthesis de novo. Placement of the prosthesis took around 30 minutes. This timeframe is similar to other methods traditionally used to close chest wall defects. The ribs can be created during the resection time, because the model is already created and may increase efficiency and saving time in reconstruction

An important strength of this study is that it uses retrospective imaging data, that is, data that was obtained from clinically indicated scans that were reconstructed with standard techniques; as such, these results are potentially replicable with advanced post-processing and therefore translational.

Further work is required to study chest wall compliance and follow-up data on patients who have had a prosthesis implanted using this proof of concept technique. Mechanical properties of neo-ribs have previously been tested and spirometry derived assessments of compliance have also been tested before and after titanium sternal implantation.[25,26] We believe that four-dimensional magnetic resonance imaging scanning will provide functional information on the benefit this technique has on respiratory mechanics.

Conclusions

This case series demonstrates that it is possible to create a chest wall prosthesis that is patient specific and has both a solid component, which provides protection, and a flexible material that provides compliance. These materials have been used before and are known to be both durable and produce satisfactory patient outcomes. Applying the materials together in this way mimics the natural chest wall with the methyl methacrylate cement ribs bridging the native ribs and the expanded polytetrafluoroethylene as a continuation of the intercostal muscle layer.

Methyl methacrylate cement has been used safely for many years; now that extended chest wall resections are performed, chest wall prosthesis needs to be created with good cosmetic results that do not impair the respiratory mechanics. We have developed this 3D printing stepwise approach using methyl methacrylate cement to reproduce the exact chest wall shape to get better cosmetic results and satisfactory breathing mechanics without increasing the costs.

Contributions

All authors fulfill the four criteria according to ICMJE. The main contributions are listed below:

JS: Main author of the manuscript; AP: Substantial contributions to the design of the work and acquisition of data for the work; MJ: Drafting the work for important intellectual content; AN: Revising it critically for important intellectual content; AB: Revising it critically for important intellectual content and substantial contributions to the design of the work.

References

1 Schubert C, van Langeveld MC, Donoso LA. Innovations in 3D printing: a 3D overview from optics to organs. Br J Ophthalmol 2014;98(02):159–161

2 Ventola CL. Medical applications for 3D printing: current and projected uses. P&T 2014;39(10):704–711

3 Cui X, Boland T, D'Lima DD, Lotz MK. Thermal inkjet printing in tissue engineering and regenerative medicine. Recent Pat Drug Deliv Formul 2012;6(02):149–155

4 Kiraly L, Tofeig M, Jha NK, Talo H. Three-dimensional printed prototypes refine the anatomy of post-modified Norwood-1 complex aortic arch obstruction and allow presurgical simulation of the repair. Interact Cardiovasc Thorac Surg 2016;22(02):238–240

5 Shiraishi I, Yamagishi M, Hamaoka K, Fukuzawa M, Yagihara T. Simulative operation on congenital heart disease using rubber-like urethane stereolithographic biomodels based on 3D datasets of multislice computed tomography. Eur J Cardiothorac Surg 2010;37(02):302–306

6 Banks J. Adding value in additive manufacturing: researchers in the United Kingdom and Europe look to 3D printing for customization. IEEE Pulse 2013;4(06):22–26

7 Zopf DA, Hollister SJ, Nelson ME, Ohye RG, Green GE. Bioresorbable airway splint created with a three-dimensional printer. N Engl J Med 2013;368(21):2043–2045

8 Saijo H, Igawa K, Kanno Y, et al. Maxillofacial reconstruction using custom-made artificial bones fabricated by inkjet printing technology. J Artif Organs 2009;12(03):200–205

9 Riaz SP, Linklater KM, Page R, Peake MD, Møller H, Lüchtenborg M. Recent trends in resection rates among non-small cell lung cancer patients in England. Thorax 2012;67(09):811–814

10 Coleman FP. Primary carcinoma of the lung, with invasion of the ribs: pneumonectomy and simultaneous block resection of the chest wall. Ann Surg 1947;126(02):156–168

11 Piehler JM, Pairolero PC, Weiland LH, Offord KP, Payne WS, Bernatz PE. Bronchogenic carcinoma with chest wall invasion: factors affecting survival following en bloc resection. Ann Thorac Surg 1982;34(06):684–691

12 Trastek VF, Pairolero PC, Piehler JM, et al. En bloc (non-chest wall) resection for bronchogenic carcinoma with parietal fixation. Factors affecting survival. J Thorac Cardiovasc Surg 1984;87 (03):352–358

13 McCaughan BC, Martini N, Bains MS, McCormack PM. Chest wall invasion in carcinoma of the lung. Therapeutic and prognostic implications. J Thorac Cardiovasc Surg 1985;89(06):836–841

14 Pairolero PC, Trastek VF, Payne WS. Treatment of bronchogenic carcinoma with chest wall invasion. Surg Clin North Am 1987;67 (05):959–964

15 Stoelben E, Ludwig C. Chest wall resection for lung cancer: indications and techniques. Eur J Cardiothorac Surg 2009;35 (03):450–456

16 Downey RJ, Martini N, Rusch VW, Bains MS, Korst RJ, Ginsberg RJ. Extent of chest wall invasion and survival in patients with lung cancer. Ann Thorac Surg 1999;68(01):188–193

17 Albertucci M, DeMeester TR, Rothberg M, Hagen JA, Santoscoy R, Smyrk TC. Surgery and the management of peripheral lung tumors adherent to the parietal pleura. J Thorac Cardiovasc Surg 1992;103(01):8–12, discussion 12–13

18 Mansour KA, Thourani VH, Losken A, et al. Chest wall resections and reconstruction: a 25-year experience. Ann Thorac Surg 2002; 73(06):1720–1725, discussion 1725–1726

19 McCormack P, Bains MS, Beattie EJ Jr, Martini N. New trends in skeletal reconstruction after resection of chest wall tumors. Ann Thorac Surg 1981;31(01):45–52

20 Yushkevich PA, Piven J, Hazlett HC, et al. User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability. Neuroimage 2006;31(03):1116–1128

21 Meshlab. http://meshlab.sourceforge.net/ Website accessed on 03/11/2017

22 Suzuki K, Park BJ, Adusumilli PS, et al. Chest wall reconstruction using a methyl methacrylate neo-rib and mesh. Ann Thorac Surg 2015;100(02):744–747

23 Pastorino U, Duranti L, Scanagatta P, et al. Thoracopleuropneumonectomy with riblike reconstruction for recurrent thoracic sarcomas. Ann Surg Oncol 2014;21(05):1610–1615

24 le Roux BT, Shama DM. Resection of tumors of the chest wall. Curr Probl Surg 1983;20(06):345–386

25 Girotti A, Rosa F, Ferrotto M, Girotti P, Pastorino U. Mechanical behavior of a total chest wall prosthesis with rib-like features. Comput Methods Biomech Biomed Engin 2017;20(15): 1581–1588

26 Oswald N, Senanayake E, Naidu B, Khalil H, Bishay E. Chest wall mechanics in vivo with a new custom-made three-dimensional-printed sternal prosthesis. Ann Thorac Surg 2018;105(04): 1272–1276