Trauma Case Reports 22 (2019) 100218

Contents lists available at ScienceDirect

Trauma Case Reports

journal homepage: www.elsevier.com/locate/tcr

Case Report

3D printed modeling contributes to reconstruction of complex chest wall instability☆,☆☆,☆☆☆

John R. Bergquist[a], Jonathan M. Morris[b], Jane M. Matsumoto[b], Henry J. Schiller[a], Brian D. Kim[a,*]

[a] *Mayo Clinic Rochester, Department of Surgery, United States of America*
[b] *Mayo Clinic Rochester, Department of Radiology, United States of America*

ARTICLE INFO

Keywords:
Rib stabilization
3-d printing
chest wall reconstruction
modeling

ABSTRACT

Background: Three-dimensional printed models are increasingly used in many fields including medicine and surgery, but their use in the planning and execution of complex chest wall reconstruction has not been adequately described. In cases of non-union or prior attempts at chest wall reconstruction which have failed, there can be substantial deviations from expected chest wall anatomy. We report a novel technique for pre-operative planning and surgical execution of complex chest wall reconstruction, assisted by 3D printing. Our objective was to utilize 3-D volumetric modeling coupled with 3-D printing to produce patient-specific models for chest wall reconstruction in complex cases.
Methods: Soft tissue reconstruction 0.75 mm slice thickness computed tomography (CT) imaging data was loaded into medical CAD software for segmentation. Lung, muscle, foreign bodies, and bony structureswere separated due to the differences in density between them. The 3D volumetric mesh was then quality checked and stereolithography files (STL) were made which were able to be utilized by the 3D printer. The STL files were exported to a Objet 500 material jetting printer that utilized several UV light cured photopolymers.
Results: As an example case, we discuss a 55 year old male who underwent resuscitative thoracotomy. In the early post-operative period, he developed a pulmonary hernia in the 6th intercostal space, repaired with wire cerclage reapproximation of ribs. He developed a symptomatic mobile chest wall at the site of prior repair with additional concern for dissociated anterior cartilage. In preparation for operative repair, a 3D printed model was created, demonstrating fractured cartilage anteriorly as well a saw effect through the six and seventh ribs. An additional model was created using the normal ribs from the right side in mirror image reflection to quantify the degree and precise geometry of mal-alignment to the left chest. These models were then utilized to determine the operative approach via a thoracotomy incision to remove the cerclage wires, followed by parasternal incision, reduction and plating of the sternocostal non-union bursa Rib non-unions were plate stabilized. Repeat imaging in follow-up has demonstrated continued appropriate alignment and the patient reported improvement in his symptoms.
Conclusion: At present, the cost of 3-D printing remains substantial, but given the improved planning in complex cases, this cost may be recaptured in the reduction of operative time and

☆ Grant support: None.
☆☆ This work has not previously or concurrently been submitted for publication. The work has been presented at the 2018 Chest Wall Injury Summit in Park City, UT on March 4, 2018.
☆☆☆ No specific funding was provided for this work.
* Corresponding author at: Mayo Clinic, 200 First St. Southwest, Rochester, MN 55905, United States of America.
E-mail address: Kim.Brian@mayo.edu (B.D. Kim).

https://doi.org/10.1016/j.tcr.2019.100218
Accepted 16 June 2019
Available online 19 June 2019
2352-6440/

improved outcomes with reduced re-operation rates. We believe that the early adoption of this technology by surgeons can help improve surgical quality and provide enhanced individualized patient care. These patient-specific models facilitate identification of features which are often not detected with standard 3-D reconstructed CT rendering. Centers should pursue the integration of 3-D printed models into their practice and active collaborations between surgeons and modeling experts should be sought at every available opportunity.

Introduction

Anatomical models are increasingly utilized in planning for complex surgery as well as medical education. Computed tomography (CT) including surface shaded 3-Dimensional (3-D) reconstruction is routinely used for pre-operative planning of complex surgical procedures, but 3-D printing is not currently routine. 3-D printed models can be created by exporting DICOM Imaging data into segmentation software where the anatomy of interest is separated and color coded. The segmentation file is processed using CAD software to create a file for 3-D printing [1]. Recent advances in segmentation algorithms along with growing availability of low-cost

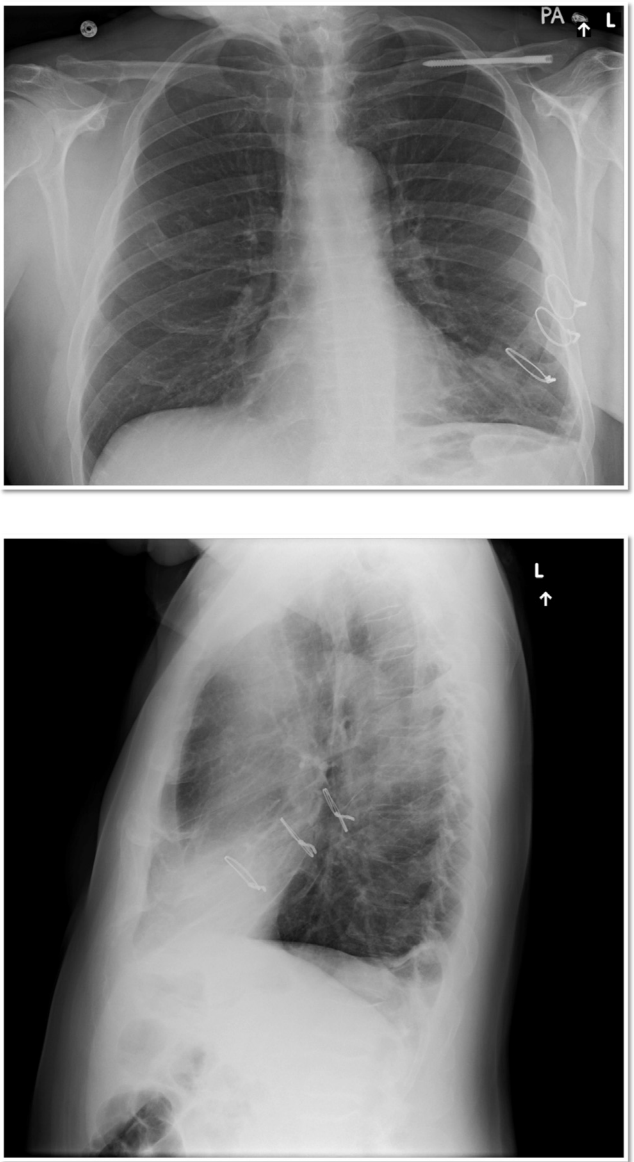

Fig. 1. Initial X-rays showing wire cerclage repair of pulmonary hernia in 6th intercostal space.

3-D printers have reduced the barrier to production of 3-D anatomical models. The use of such models can increase the surgeon's ability to plan and successfully execute complex procedures [1]. We have previously described cases utilizing these techniques to assist with cardiac mitral valve intervention, tracheal reconstruction [2], scaphoid nonunion [3], and nephrectomy [4]. However, their utilization for planning of complex chest wall reconstruction after traumatic injury has not previously been described.

Rib fracture is a common outcome of blunt chest trauma and results in substantial morbidity [5]. The utilization of open reduction and internal fixation, known alternatively as surgical stabilization of rib fracture (SSRF) has been utilized since at least the 1950's [6]. Techniques have evolved quite substantially in that time from the initial approach of paracostal wire stitches to more modern techniques using plates and bicortical screw fixation devices [7]. In cases of non-union, delayed repair, or re-operation for symptoms in the setting of prior inadequate fixation, chest wall geometry may be substantially altered from normal and require advanced pre-operative planning in order to facilitate adequate reduction and ultimately successful repair [8]. Although utilization of 3-D printing to create chest wall prostheses in complex cases has been previously investigated [9–11], the use of commerically available software

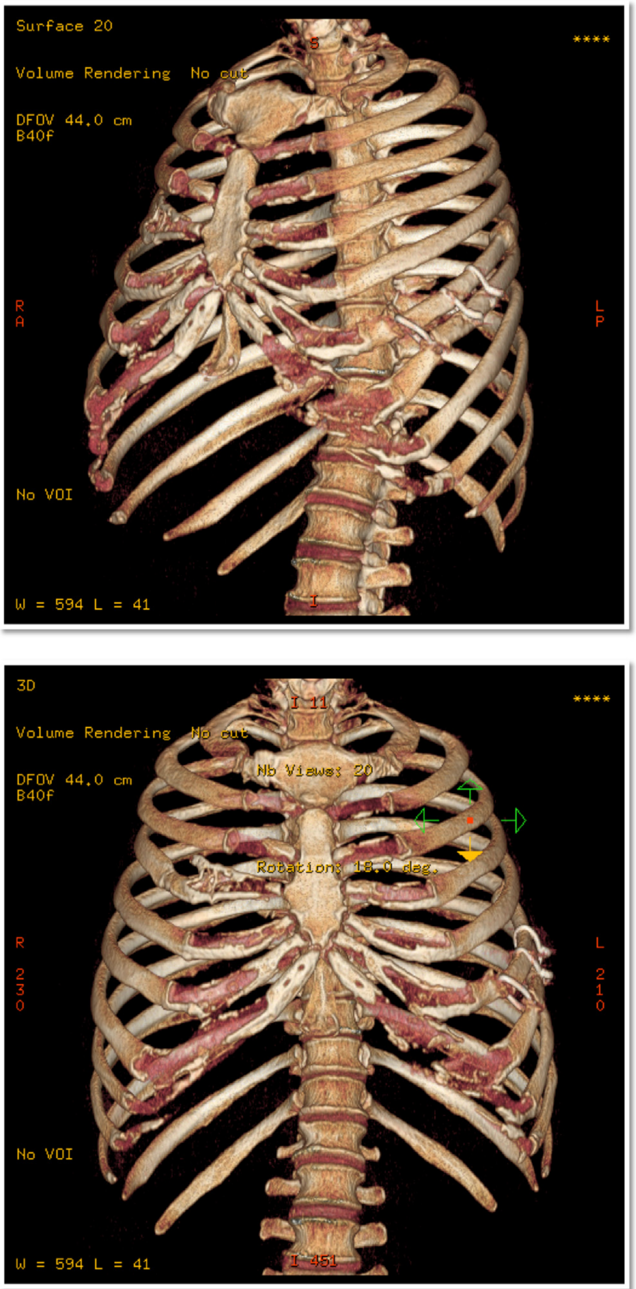

Fig. 2. Initial CT scan showing lateral nonunion but inadequately visualizing costochondral nonunion in the medial aspect.

and 3D printing technology to facilitate complex reconstruction using standard surgical components has not been previously described. Given the compound curvature and dynamic anatomy of the chest wall, the utilization of patient specific 3D printed models to facilitate detailed operative planning prior to undertaking complex non-union or re-operative chest wall repair with SSRF presents a substantial opportunity. Here we present an example of the use of 3-D printing techniques to facilitate surgical planning of complex chest wall reconstruction.

Procedure and techniques

Computed tomography (CT) imaging data reconstructed to 0.75 mm slice thickness is loaded into medical CAD software (Materialise - Leuven, Belgium) for segmentation. Lung, muscle, foreign bodies, cartilage and bony structures are segmented using both automatic tools based on density and manual tools. The 3-D volumetric mesh is converted into Stereolithography files (STL) which are exported for 3-D printing. The STL files are back-checked against the source imaging data as part of a quality assurance process. The 3-D printer software then slices the data into ultra thin layers which are laid down layer by layer in sub-millimeter portions. Our STL files were exported to an Objet 500 (Stratasys, Eden Prairie MN) material jetting printer that utilizes several UV light cured photopolymers. This printer works by laying down different photopolymers in droplets and then curing them with UV light allowing it to print in multiple materials simultaenously including mulitple colors and flexibitilites as well as clear. This type of printer offers several advantages when reconstructing the chest wall including flexible cartilage and color-coded anatomy as well as foreign bodies.

As an example, we present a 55 year old male who presented to his local emergency department at another institution after having been stabbed in the left chest. He suffered a cardiac arrest and underwent resuscitative thoracotomy. A laceration of the left ventricle was repaired. During the initial procedure, his ribs were re-approximated with #1 ethibond sutures. In the post-operative period, he developed a pulmonary hernia in the 6th intercostal space which was repaired at a second operation at his local hospital using the technique of wire cerclage (Fig. 1). The use of wire cerclage was preferred by the local surgeon as a means to better appoximate the ribs due to ‘resistance to closure’ during this second operation. An interval of 2 months passed after the chest wall cerclage repair before the patient presented to our institution as a self-referral with complaints of ongoing pain and sensation of clicking in the left chest wall when breathing. He had pain with any cough, laugh, strain or stretch. CT imaging was obtained illustrating substantial alteration in the alignment of the sixth and seventh left ribs, including non-union (Fig. 2). On physical examination, there was both mobile nonuion of his ribs as well as concern for instability at the ipsilateral costal cartilage although this was not detected on the initial CT scan. The decision was made to attempt repair of his chest wall using plates and bicortical screws. In preparation, 3-D volumetric images as well as 3-D printed models were made utilizing the methods outlined above (Fig. 3). This model consisteted of vertebral bodies, ribs, cerclage wires, and cartilage. The model demonstrated a clear disruption at the costosternal joint which, in conjunction with the seton effect of the cerclage wires, was distorting the alignment of the left chest. An additional model was created using mirror image right ribs to overlie on the abnormal left ribs to quantify the degree and geometry of mal-alignment (Fig. 4). These models were studied and used to determine the operative approach utilizing a thoracotomy incision to remove the cerclage wires, followed by parasternal incision, reduction and plating of the sternocostal dissociation first to improve overall thoracic cage

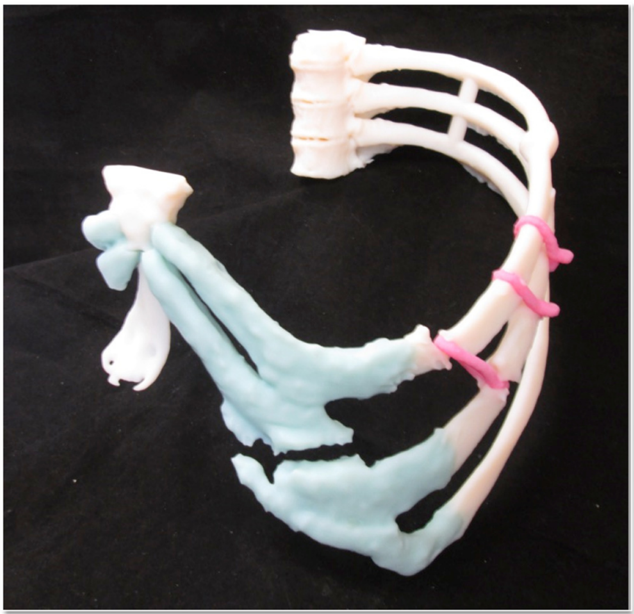

Fig. 3. Model photos demonstrate non-union at the costal cartilage.

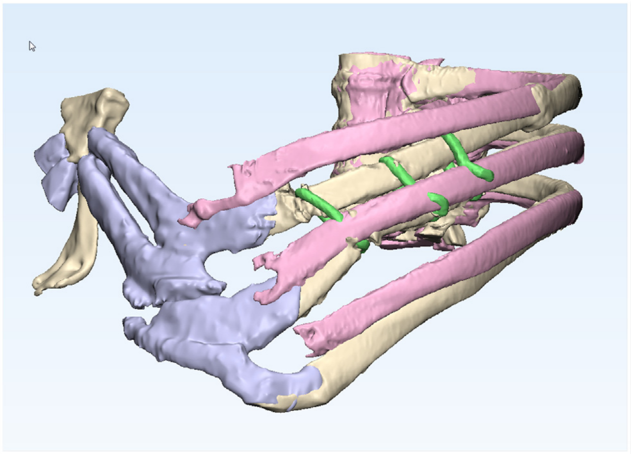

Fig. 4. Overlaid model demonstrates the degree of mal-alignment based on mirror image data from the contra-lateral side.

alignment (Fig. 5). The rib non-unions were then repaired individually with appropriate anatomic alignment (Fig. 6). Repeat imaging in follow-up has demonstrated continued good alignment and the patient reports resolution of his symptoms.

Discussion

Chest wall reconstruction can be challenging [12], fraught with difficulties including malalignment, altered geometry, patient compensatory muscular hypertrophy, and spinal changes [5]. Elderly patients or those with barriers to bone healing and remodeling have an increased risk [5] for subsequent nonunion despite proper reduction and stabilization. Meticulous surgical planning is essential for the achievement of optimal outcomes. The advent of accessible, hospital based 3-D modeling can facilitate pre-operative understanding of the underlying anatomy and optimize surgical planning for implanting materials prior to surgical incision [13,14]. Without 3-D models, each individual case requires the surgeon, using two dimensional non-life-size images, to create a 3-D model mentally and then tranlsate that to a life size plan. The patient-specific life size 3-D printed model allows the surgeon to more easily comprehend and understand the anatomy without mental gymnastics. These models offer a life size, multimaterial, tactile approach that was heretofore inaccessible. Secondarily, it allows the surgeon to pre-operatively bend plates to the patient's specific anatomy, preprocedurally practice the osteotomies, and preoperatively have the plates sterilized, thus saving operative time. The utilization of individual custom 3-D models for these types of cases offers personalized medicine for this patient population. In particular, for the complex geometry of chest wall reconstruction, 3-D printing can play an important role and provide substantial benefit as it did in our example case [9,11]. In particular, without the input of the 3-D model, we would not have identified the need for stabilizaation repair of the costosternal disruption prior to undertaking the rib plating. Additionally, if we had undertaken the rib plating procedure first, guided only by standard 3-D reconstructed CT data, final chest wall alignment might well have remained sub-optimal and may have required re-operation.

Surgeons are ideally positioned both to utilize and to advance the techniques of 3-D anatomic modeling in cases where it can be utilized to improve patient care. Barriers to the utilization of 3-D printing in surgical fields continue to be present in the form of time, cost, and expertise. However, as 3-D printing becomes more commonplace, the utilization of this technique will continue to increase and become progressively more accessible for the planning and execution of complex chest wall reconstruction. At our institution, we have built an in-hopsital centralized 3-D printing facility to serve the surgical theater when complex cases arise. This allows point-of-care multidisciplinary collaboration and 3-D printing additive manufacturing expertise to the surgeons involved which accelerates innovative personalized care.

In addition to the operative planning support which 3-D modeling can provide, there are real educational benefits. Prior studies have shown that a substantial portion of learners prefer some tactile component [15], and the utilization of 3-D modeling in renal tumors has shown that learners are better able to understand surgical geometry using a printed model than CT data [16]. In this study, trainees in particular expressed a strong preference for the printed models as learning tools. In fact, another study in renal cancer provided anecdotal evidence that the implications of these findings extend not only to trainee education but also to patients and families [17], and a follow-up report demonstrated that individualized 3-D printouts used for patient counseling facilitated patients' improved understanding of their disease in multiple areas including physiology, anatomy, tumor characteristics, and the surgical plan [18].

At present, the cost of 3-D printing remains substantial, but given the improved planning in complex cases, this cost may be recaptured in the reduction of operative time and improved outcomes with reduced re-operation rates. While the scope of segmentation software, medical computer aided design, and 3-D printers is too large for this report, there exists low-cost entry-level radiology software that allows 3D printing STL file exportation. The 3-D printing prices depend on number of colors, materials, and build size needed for select cases. For smaller, single material print jobs, entry-level, accurate, dependable printers can be bought for

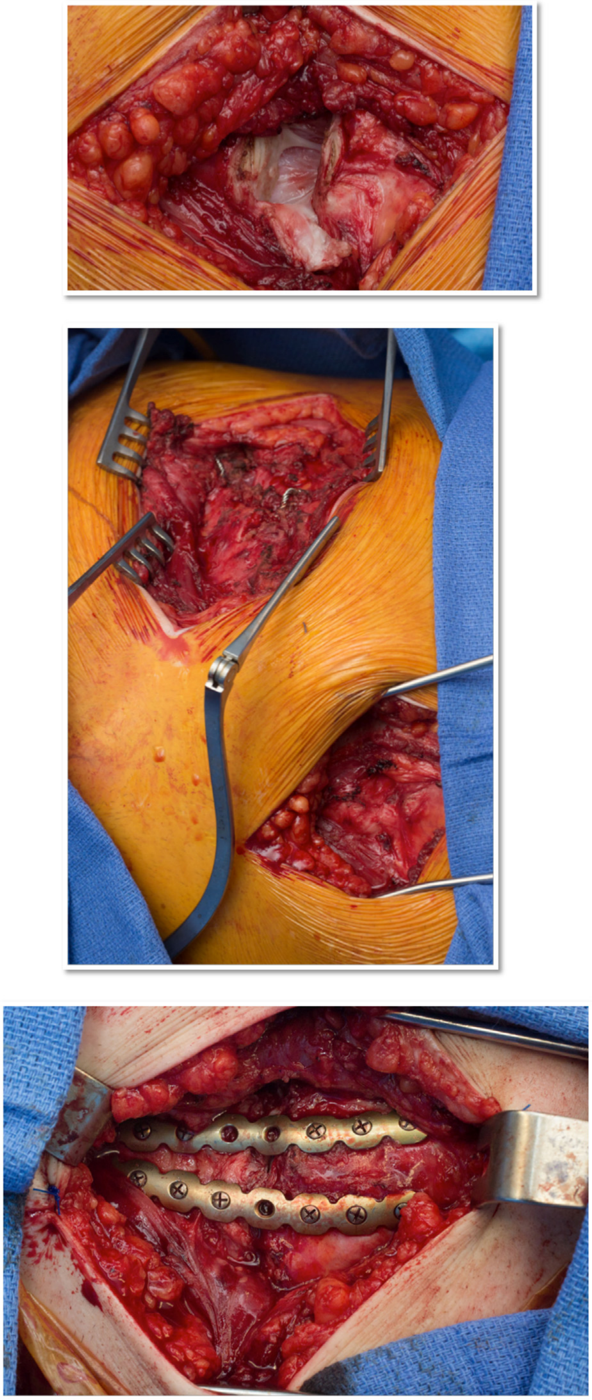

Fig. 5. Intra-operative photos show parasternal incision and plating in addition to plating of ribs 5 and 6.

under $3000, but industrial, large build volume printers range from $100,000 to $500,000. The continued advancement of technology and the explosive growth in this field suggest that within only a few years the cost will be reduced to a point where 3-D printing may be achievable in all routine cases where complex 3-D geometry is visualized. We believe that the early adoption of this technology by surgeons can help improve surgical quality and provide more individualized patient care. Centers should pursue the integration of 3-D printed models into their practice and active collaborations between surgeons and modeling experts should be sought at every available opportunity.

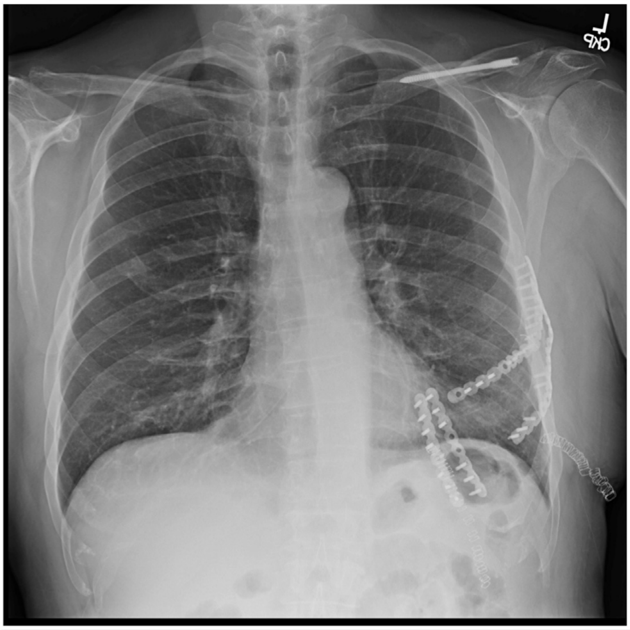

Fig. 6. Post-operative film showing reduced and plated ribs and costosternal articulation.

Authorship

Study Design and Concept: Kim, Schiller, Bergquist, Matsumoto, Morris.
Data Acquisition, Analysis and Interpretation: Kim, Schiller, Bergquist, Matsumoto, Morris.
Manuscript preparation and revision: Bergquist, Kim, Schiller, Matsumoto, Morris.

Declaration of Competing Interest

All authors declare no conflicts of interest.

Acknowledgements

In-kind material support from the Mayo Clinic Rochester Department of Radiology is gratefully acknowledged.

References

[1] J.A. Dearani, M. Gold, B.C. Leibovich, K.A. Ericsson, K.R. Khabbaz, T.A. Foley, et al., The role of imaging, deliberate practice, structure, and improvisation in approaching surgical perfection, J Thorac Cardiovasc Surg [Internet] 154 (4) (2017) 1329–1336 Oct [cited 2017 Nov 6]. Available from http://www.ncbi.nlm.nih.gov/pubmed/28554678.
[2] K. Balakrishnan, S. Cofer, J.M. Matsumoto, J.A. Dearani, R.P. Boesch, Three-dimensional printed models in multidisciplinary planning of complex tracheal reconstruction, Laryngoscope 127 (4) (2017) 967–970 Internet. Apr [cited 2017 Nov 6. Available from http://www.ncbi.nlm.nih.gov/pubmed/27753107.
[3] M.T. Houdek, J.M. Matsumoto, J.M. Morris, A.T. Bishop, A.Y. Shin, Technique for 3-dimensional (3D) modeling of osteoarticular medial femoral condyle vascularized grafting to replace the proximal pole of unsalvagable scaphoid nonunions, Tech Hand Up Extrem Surg [Internet] 20 (3) (2016) 117–124 Sep [cited 2017 Nov 6]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/27466049.
[4] Westerman ME, Matsumoto JM, Morris JM, Leibovich BC. Three-dimensional printing for renal cancer and surgical planning. Eur Urol Focus [Internet]. 2016 Dec 15 [cited 2017 Nov 6];2(6):574–6. Available from: http://www.ncbi.nlm.nih.gov/pubmed/28723485
[5] M. Sirmali, H. Türüt, S. Topçu, E. Gülhan, U. Yazici, S. Kaya, et al., A comprehensive analysis of traumatic rib fractures: morbidity, mortality and management, Eur J Cardiothorac Surg [Internet] 24 (1) (2003) 133–138 Jul [cited 2017 Nov 11]. Available from http://www.ncbi.nlm.nih.gov/pubmed/12853057.
[6] M. Bemelman, M. Poeze, T.J. Blokhuis, L.P.H. Leenen, Historic overview of treatment techniques for rib fractures and flail chest, Eur. J. Trauma Emerg. Surg. 36 (5) (2010) 407–415 Internet. Oct 23 [cited 2017 Nov 11. Available from http://www.ncbi.nlm.nih.gov/pubmed/21841952.
[7] S.F. Marasco, A.R. Davies, J. Cooper, D. Varma, V. Bennett, R. Nevill, et al., Prospective randomized controlled trial of operative rib fixation in traumatic flail chest, J Am Coll Surg [Internet] 216 (5) (2013) 924–932 May [cited 2017 Nov 11]. Available from http://www.ncbi.nlm.nih.gov/pubmed/23415550.
[8] Reisenauer JS, Kim BD, Cassivi SD, Cross WW, Morris DS, Schiller HJ. Repair of symptomatic non-union rib fractures: outcomes from a contemporary thoracic surgical series. J. Cardiothorac. Surg. [Internet]. BioMed Central; 2015 Dec 16 [cited 2017 Nov 11]; 10(S1):A205. Available from: http://cardiothoracicsurgery.biomedcentral.com/articles/ https://doi.org/10.1186/1749-8090-10-S1-A205.
[9] J. Moradiellos, S. Amor, M. Córdoba, G. Rocco, M. Vidal, A. Varela, Functional chest wall reconstruction with a biomechanical three-dimensionally printed implant, Ann Thorac Surg [Internet] 103 (4) (2017) e389–e391. Apr [cited 2017 Oct 27]. Available from http://www.ncbi.nlm.nih.gov/pubmed/28359508.
[10] J.L. Aranda, M.F. Jiménez, M. Rodríguez, G. Varela, Tridimensional titanium-printed custom-made prosthesis for sternocostal reconstruction, Eur J Cardio-Thoracic Surg [Internet] 48 (4) (2015) e92–e94 Oct [cited 2017 Oct 27]. Available from http://www.ncbi.nlm.nih.gov/pubmed/26242897.
[11] L. Wang, T. Cao, X. Li, L. Huang, Three-dimensional printing titanium ribs for complex reconstruction after extensive posterolateral chest wall resection in lung

cancer, J Thorac Cardiovasc Surg [Internet] 152 (1) (2016) e5–e7 Jul [cited 2017 Oct 27]. Available from http://www.ncbi.nlm.nih.gov/pubmed/27045041.
[12] D.L. Ciraulo, D. Elliott, K.A. Mitchell, A. Rodriguez, Flail chest as a marker for significant injuries, J Am Coll Surg [Internet] 178 (5) (1994) 466–470 May [cited 2017 Nov 13]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/8167883.
[13] Q. Ling, E. He, H. Ouyang, J. Guo, Z. Yin, W. Huang, Design of mulitlevel OLF approach ("V"-shaped decompressive laminoplasty) based on 3D printing technology, Eur. Spine J. 27 (Suppl 3) (2018) 323–329, https://doi.org/10.1007/s00586-017-5234-0 Epub 2017 Jul 27. Available from: http://www.ncbi.nlm.nih.gov/pubmed/28752243.
[14] R.J. Mobbs, M. Coughlan, R. Thompson, C.E. Sutterlin, K. Phan, The utility of 3D printing for surgical planning and patient-specific implant design for complex spinal pathologies: case report, J Neurosurg Spine [Internet] 26 (4) (2017) 513–518. Apr [cited 2017 Oct 27]. Available from http://www.ncbi.nlm.nih.gov/pubmed/28106524.
[15] R.A. Preece, A.C. Cope, Are surgeons born or made? A comparison of personality traits and learning styles between surgical trainees and medical students, J Surg Educ 73 (5) (2016) 768–773.
[16] M. Knoedler, A.H. Feibus, A. Lange, M.M. Maddox, E. Ledet, R. Thomas, et al., Individualized physical 3-dimensional kidney tumor models constructed from 3-dimensional printers result in improved trainee anatomic understanding, Urology 85 (6) (2015) 1257–1261.
[17] J.L. Silberstein, M.M. Maddox, P. Dorsey, A. Feibus, R. Thomas, B.R. Lee, Physical models of renal malignancies using standard cross-sectional imaging and 3-dimensional printers: a pilot study, Urology 84 (2) (2014) 268–272.
[18] J.C. Bernhard, S. Isotani, T. Matsugasumi, V. Duddalwar, A.J. Hung, E. Suer, et al., Personalized 3D printed model of kidney and tumor anatomy: a useful tool for patient education, World J. Urol. 34 (3) (2016) 337–345.