

Original Article

Virtual preoperative planning and 3D printing are valuable for the management of complex orthopaedic trauma

Abhishek Mishra ^{a,*}, Tarun Verma ^a, Abhishek Vaish ^a, Riya Vaish ^a, Raju Vaishya ^b, Lalit Maini ^a^a Department of Orthopaedics and Joint Replacement Surgery, Maulana Azad Medical College, Lok Nayak Hospital, New Delhi 110001, India^b Department of Orthopaedics and Joint Replacement Surgery, Indraprastha Apollo Hospital, Sarita Vihar, New Delhi 110076, India

ARTICLE INFO

Article history:

Received 23 February 2019

Received in revised form

1 August 2019

Accepted 16 August 2019

Available online 7 September 2019

Keywords:

Three-dimensional printing

Bone fractures

Fracture dislocation

X-ray computed tomography

ABSTRACT

Purpose: The technology of 3D printing (3DP) exists for quite some time, but it is still not utilized to its full potential in the field of orthopaedics and traumatology, such as underestimating its worth in virtual preoperative planning (VPP) and designing various models, templates, and jigs. It can be a significant tool in the reduction of surgical morbidity and better surgical outcome avoiding various associated complications.

Methods: An observational study was done including 91 cases of complex trauma presented in our institution requiring operative fixation. Virtual preoperative planning and 3DP were used in the management of these fractures. Surgeons managing these cases were given a set of questionnaire and responses were recorded and assessed as a quantitative data.

Results: In all the 91 cases, where VPP and 3DP were used, the surgeons were satisfied with the outcome which they got intraoperatively and postoperatively. Surgical time was reduced, with a better outcome. Three dimensional models of complex fracture were helpful in understanding the anatomy and sketching out the plans for optimum reduction and fixation. The average score of the questionnaire was 4.5, out of a maximum of 6, suggesting a positive role of 3DP in orthopaedics.

Conclusion: 3DP is useful in complex trauma management by accurate reduction and placement of implants, reduction of surgical time and with a better outcome. Although there is an initial learning curve to understand and execute the VPP and 3DP, these become easier with practice and experience.

© 2019 Chinese Medical Association. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Introduction

The significance of preoperative planning is of paramount importance in the management of orthopaedic trauma. In complex fracture patterns, different strategies are required to approach and manage. Preoperative planning can play a significant role in reducing surgical duration and morbidity in these cases. Preoperative surgical planning is still not practiced routinely as much as it is recommended in the literature. Reasons for this may be the cost, effort and time investment required in preoperative planning. Methods for making it more feasible and accessible can be a lot beneficial to the younger surgeons in improving their surgical skills and practice.

3D printing (3DP) technology has recently penetrated and influenced the healthcare in a revolutionary manner. The Caritas Europa (CE) and US Food and Drug Administration (FDA) have approved and licensed a group of 3DP-based patient-specific osteotomy instruments, orthopaedic and dental implants for clinical use.¹ With the help of imaging techniques like computed tomography (CT) or magnetic resonance imaging (MRI) scans, 3D models of body organs can be constructed and printed using a 3D printer. 3DP technology has already established itself in various other fields like dental surgery, maxillofacial reconstruction, cranioplasty, and vascular surgery. In complex orthopedic trauma, virtual preoperative planning (VPP) and 3DP can be helpful in understanding the anatomy of the fractures and planning out a strategy. Accordingly, it may increase the efficacy and reduce surgical morbidity.

Methods

In this two-center based observational study, we consecutively managed 91 complex fractures which presented to our

* Corresponding author.

E-mail address: mishra.abhishek85@gmail.com (A. Mishra).

Peer review under responsibility of Chinese Medical Association.

institutions from 1st July 2017 to 31st December 2019, with the help of VPP and 3DP. These 91 complex orthopedic trauma cases were divided into 12 categories: respectively (1) acetabular fracture, $n = 60$; (2) nonunion distal tibia, $n = 1$; (3) tibial plateau fracture, $n = 10$; (4) cervical spine fracture, $n = 3$; (5) combined convergent and divergent carpo-metacarpal fracture dislocation, $n = 1$; (6) malunited fracture acetabulum, $n = 4$; (7) shoulder fracture dislocation, $n = 4$; (8) complex intra-articular elbow fracture, $n = 2$; (9) posttraumatic elbow deformity, $n = 1$; (10) comminuted distal radius fracture, $n = 2$; (11) posttraumatic knee deformity, $n = 2$ and (12) femoral head fracture, $n = 1$. Wide regions are involved, including the pelvis and hip, spine, knee, shoulder, elbow and wrist joints. Various surgeries like VPP and 3DP were applied by multiple surgeons of varying experience for the management of these injuries.

The following steps were used to create virtual 3D models and 3D printed models:

1. Non-contrast computed tomography (NCCT) scans of complex fractures were obtained and digital imaging and communications in medicine (DICOM) images were exported from that data.
2. These DICOM images were then transferred to Mimics™ (Materialise, Belgium) software.
3. Threshold was done to separate bone from surrounding soft tissue by giving it a particular color.
4. The desired bone part was then separated from the rest of the bone by erasing the surrounding bone using “edit mask” command.
5. Segmentation was done where the desired bone parts were distinguished from the rest of the bone by giving them separate colors.
6. The segmented part was converted into a virtual 3D model using “calculate 3D” command.
7. The virtual model was then exported from Mimics software as an STL file, which was further transferred to 3-matics™ (Materialise, Belgium) software and designed accordingly.
8. The desired files which can be a 3D bone model, pre-contoured plate template or a guiding jig were then exported as STL files.
9. The STL files were converted into G-codes using “3D slicer” software.
10. The G-code file was then 3D printed in a fused deposition modeling (FDM) type 3D printer using polylactic acid (PLA) material.

All the cases were analyzed on a set of the questionnaire with six questions. Each question had two responses, either yes or no. Yes response was awarded as 1 and No response was awarded as 0. So, the scale of response for every case was from 0 to 6 with 0 being the minimal response and 6 being the maximal response. The averages of all the responses were calculated and analyzed on the scale of 0–6. Responses to the following set of questions asked to operating surgeons after surgery were recorded.

Question 1. Do you think this process helped in reducing the surgical time?

Question 2. Did it change or influence surgical plan?

Question 3. Did it improve inventory management?

Question 4. Was the application of 3DP feasible?

Question 5. Did postoperative X-ray deviate from planned?

Question 6. Would you recommend the use of 3DP in the future?

Case examples

Case 1

NCCT pelvis of a 35-year-old male with T-type acetabular fracture requiring operative fixation was obtained. Virtual 3D model of acetabular fracture was created. The virtual reduction was done, and plate templates matching the contour of the reduced fracture were designed virtually. These pre-contoured plate templates were then 3D printed and used to contour the acetabular plates preoperatively. This exercise reduced surgical time and improved the outcome (Fig. 1).

Case 2

A 20-year-old male, with malunited proximal tibia fracture for 1.5 years, presented with pain in the affected knee. The patient was planned for open reduction, osteotomy and internal fixation with a plate. The malunited part was reduced, and a pre-contoured plate template was designed virtually, and 3D printed. This template was used to guide contouring of proximal tibial plate preoperatively which reduced surgical time with a better reduction in post-operative X-rays (Fig. 2).

Case 3

A 45-year-old male presented with a proximal humerus fracture requiring operative intervention. Pre-contoured plate template was designed virtually over the reduced fracture, and 3D printed. This plate template was used to guide contouring of proximal humerus plate preoperatively. It was useful in better understanding of fracture and preoperative planning with better surgical outcome (Fig. 3).

Results

In all the 91 cases, where VPP and 3DP was used, the surgeons were satisfied with the outcome which they got intraoperatively and postoperatively. Surgical time was reduced, with a better outcome. 3D models of complex fracture were helpful in understanding the anatomy and sketching out the plans for optimum reduction and fixation. The average score of the questionnaire was 4.5, out of a maximum of 6. It indicates that all the surgeons found it to be beneficial in preoperative planning, reducing the surgical duration and achieving a better postoperative outcome (Table 1). Acute, complex acetabular fractures accounted for about 65.9% (60/91) of all the cases in this series. Also, there were four malunited acetabular fractures. Tibial plateau fractures were the second highest number of cases (10/91). Due to the complex anatomy of acetabular and proximal tibial fractures and need for accurate anatomical reduction, pre-contoured patient-specific plates designed from 3DP turned out to be very useful in decreasing the surgical duration and better surgical outcome. Surgical duration was reduced significantly in our case series in about 75.0% of case categories (9 out of 12) but was not very helpful in the modification of surgical plan (only 3 out of 12).

Discussion

Although the existence of 3DP technology dates back to the 1980s, 3DP has been introduced only recently to some fields of medicine, as a new revolutionizing technology which might influence healthcare. This technology was introduced initially in the engineering and technology sector, but now its scope has penetrated the medical field. The 3DP, also called as ‘additive manufacturing (AM)’ or ‘rapid prototyping’ can now be considered

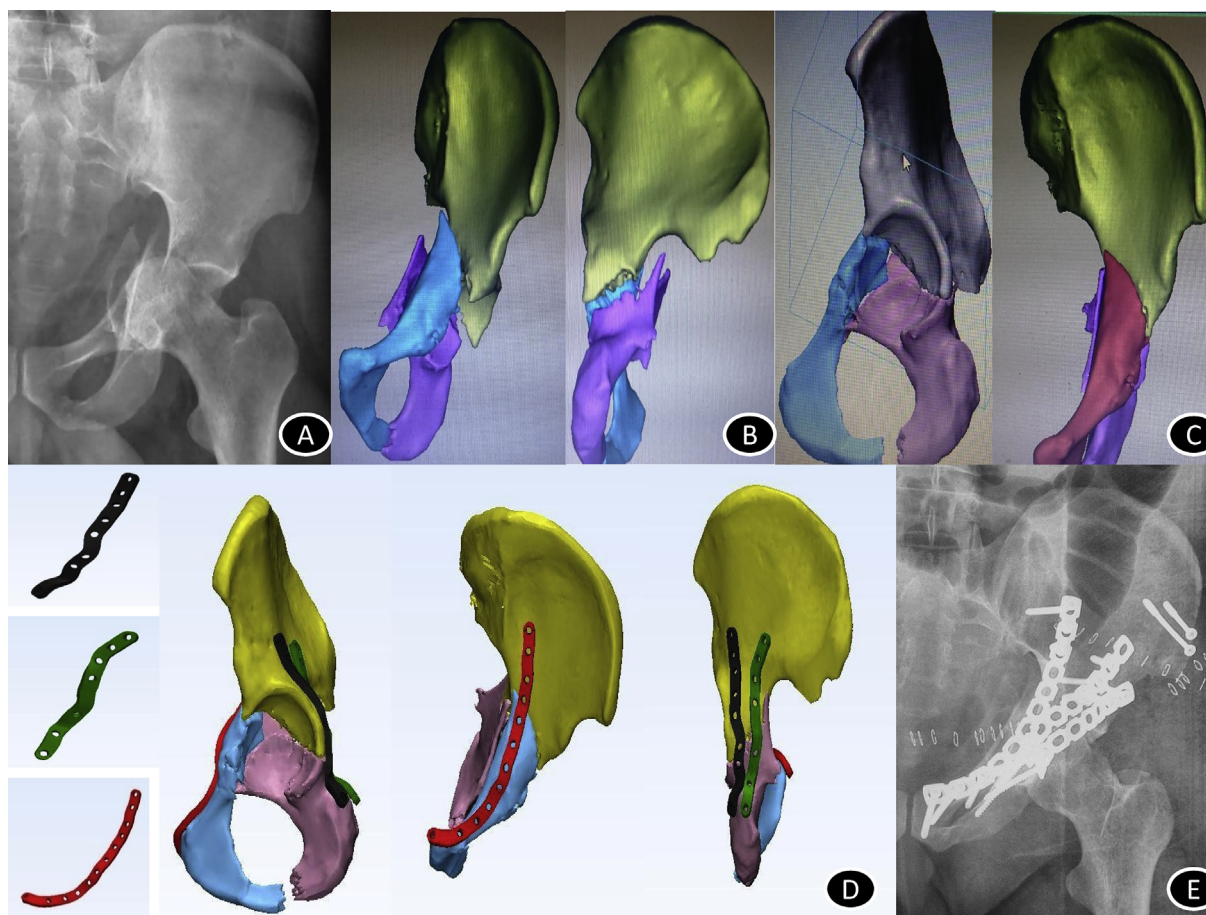


Fig. 1. Surgical planning of a complex acetabular fracture case. (A) Preoperative X-ray; (B) 3D model of acetabular fracture; (C) Virtual reduction of fracture done; (D) Pre-contoured plate designed over reduced acetabular fracture; (E) Postoperative X-ray.

as the “second industrial revolution,” and it seems especially right for orthopaedic trauma surgery.² There are various 3DP devices available which work on either an additive or subtractive principles. Mostly, AM is used to create bone models, where the material is added layer by layer to manufacture a model. Several materials can be used to make a 3D model, like acrylonitrile-butadiene-styrene (ABS) printable polymers, plastics (PLA, TPTE, resin, high detail resin flexible, nylon) and metal composite (aluminum, bronze, copper, brass, gold, titanium).³

Orthopaedics is one of the areas where VPP and 3DP have shown excellent results and proved to be beneficial for young surgeons in helping them to improve their skills, as a part of their clinical practice. 3DP in orthopaedics can be applied in various ways like designing a 3D model of complex fracture (for a better understanding of doctor as well as of the patient), planning a strategy (to fix the fracture), teaching, presentation, and surgical decision making. Based on the symmetry of the human anatomy, or by using the human anatomy data in the database, 3D images of the bones can also be reversed or mimicked at the missing parts. It assists the conventional mechanical processing to manufacture bone prostheses that can be implanted into human body.¹ By using the 3DP techniques, the Ninth People's Hospital of Shanghai Jiaotong University School of Medicine designed custom-made prostheses for the hemipelvis reconstruction after hemipelvectomy and reconstruction of a severe acetabular bone defect in hip revision surgery.^{4,5} 3DP based patient-specific instrumentation (PSI) and jigs have been designed and studied in orthopaedics. Researchers from Kunming General Hospital have demonstrated the usefulness of a

novel rapid prototyping drill template for cervical pedicle screw placement in cadaver spine specimens and satisfactory effectiveness in their clinical practices.^{6,7} Maini et al.⁸ have designed pre-contoured templates for plates used in acetabular fracture fixation with the help of VPP and 3DP and studied its efficacy and accuracy. Development of orthopaedic implants and prosthesis based on rapid prototyping has been tried successfully in the past, and more such studies are going on. 3DP can also produce an implant or prosthesis with porous nature where the size of pores can be pre-decided which can be helpful in decreasing elastic modulus of implant material, reduce stress shielding and promote the integration between metal and bones at the surface of the implants. FDA has approved the InteGrip®, an acetabular cup manufactured by Exactech with a titanium alloy with a porous surface manufactured using 3DP in 2010 and the Tesera® Standalone anterior lumbar interbody fusion cage, which was manufactured by Renovis using 3DP in 2013.¹ The researchers from the Fourth Military Medical University Affiliated Xijing Hospital and the Shanghai Jiaotong University have successfully shown the osteointegration under diabetic conditions using chitosan/hydroxyapatite composite coating on 3DP-based porous titanium surfaces.^{9,10}

In the present study, we have compiled various cases of complex trauma considering challenges which are faced generally associated with their management and tried to get a solution with VPP and 3DP techniques. Surgeons who used rapid prototyping in their surgeries came with a positive response regarding the efficacy of this procedure and recommended its use in future for various kind of trauma. Jigs designed for placement of cervical pedicle screws

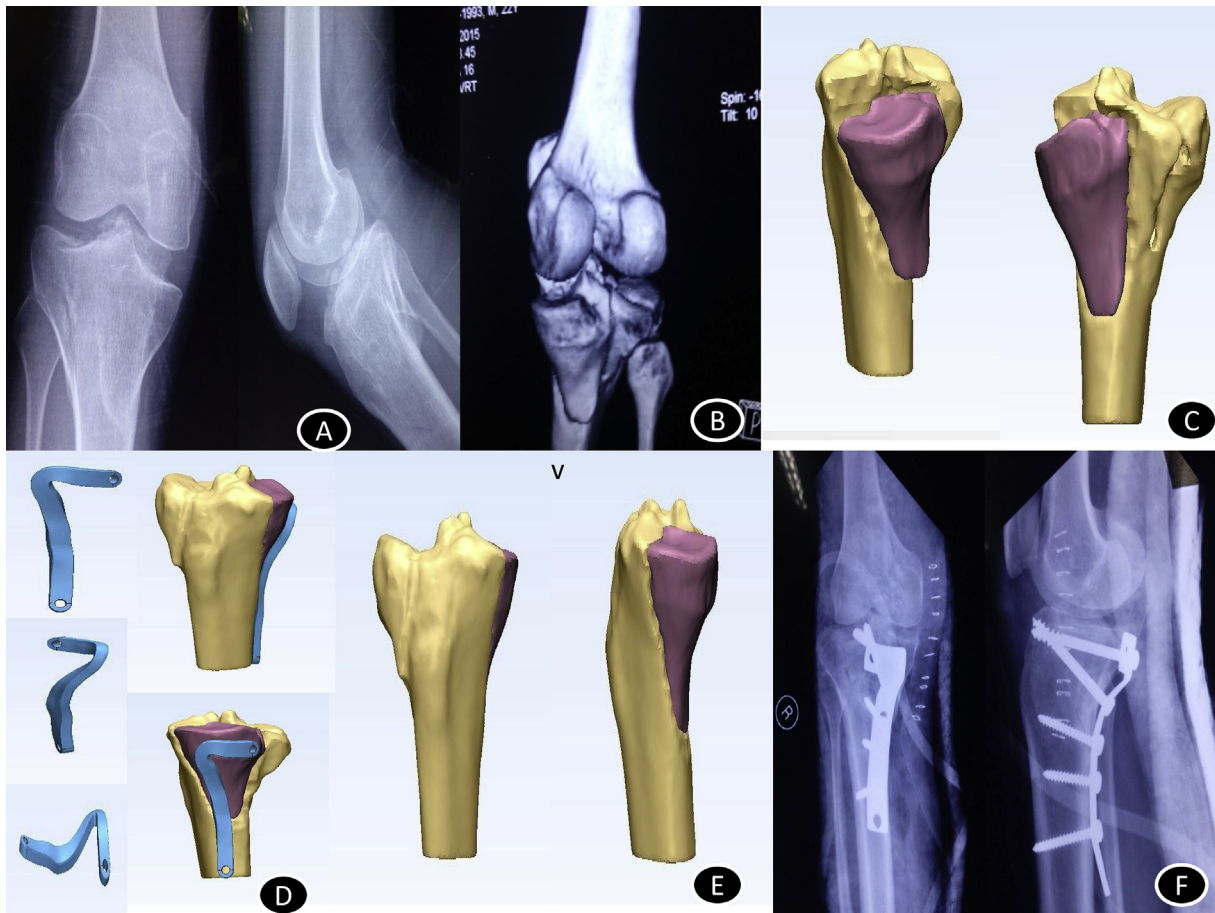


Fig. 2. Virtual preoperative planning of a malunited tibial plateau fracture. (A) Preoperative X-ray of malunited tibial plateau fracture; (B) 3D reconstruction from non-contrast computed tomography; (C) Virtual 3D model designed from DICOM images; (D) Pre-contoured plate designed; (E) Reduction done virtually; (F) Postoperative X-ray.

save surgical time and reduce unnecessary exposure in image fluoroscopy. It is reported that each minute of exposure (60 shots) is equivalent to one computed radiography exposure or 4 Rads of radiation and that many periarticular fracture fixation scenarios require many minutes of these exposures.¹¹

Acetabular component placement in primary total hip replacement (THR) can be guided with surrounding landmarks like transverse acetabular ligament (TAL) but in complex cases where landmarks have been distorted like in a case we did in malunited acetabular fracture where cup placement was guided with a jig designed on 3D model turned out to be very useful. Anteversion of the cup was well within safe range as suggested by Lewinnek.¹² In such complex cases, the surgeon has to keep in mind about the biomechanics of hip, bone defect and plan reconstructive technique accordingly. Similarly, in the case of revision THR, it is also essential to know the cause of failure, strategy for implant removal, appropriate implant required for adequate reconstruction.^{13,14} In both these conditions, having a real size model of the area helps to understand the pathoanatomy and bone defect better.¹⁵ With newer metal printers and the capability of printing biocompatible materials now being easily accessible, many companies now have developed 3DP of the wedges and cones, and patient-specific hip and knee implants may become much more common in coming years.¹⁶

The benefit of rapid prototyping would require consideration of both the complex nature of the case and surgeon experience. The complexity of the fracture increases the information gained from

the model, which may exceed that obtained from radiographs or routine CT scans.¹⁷ Technology for management of such complex cases seems easy and practical, benefiting both the surgeon and patient and is worth the time and expenditure required.

This method of VPP and 3DP used in our study was done by the operating surgeon team without any help from an engineer or any technical person guiding the use of computer software. It avoided the understanding barrier of an engineer about the patient's anatomy, the complexity of trauma, and intraoperative complications expected during surgery. We believe that a surgeon performing such technical exercise with the knowledge of the anatomy of fracture and expected outcome produces better results. Also, after initial difficulties with a learning curve, the time duration for VPP and 3DP is reduced to a significant level where this can be used in complex trauma cases which are to be fixed as early as possible. The apprehension of fixation of complex trauma to the earliest can be efficiently dealt with the help of VPP and 3DP in a shorter interval of time and get the patient ready for fixation with sound preoperative planning.

VPP and 3DP not only help operating surgeon team to understand the fracture's anatomy and planning out an approach for fixation of a complicated fracture but also help the patient understand and educate him about his condition and explaining the treatment protocol along with other alternative options. It can prove to be a significant tool to improve the doctor-patient relationship and to build patient's trust in the doctor and his offered treatment. Also, this technique can be useful as an academic tool for

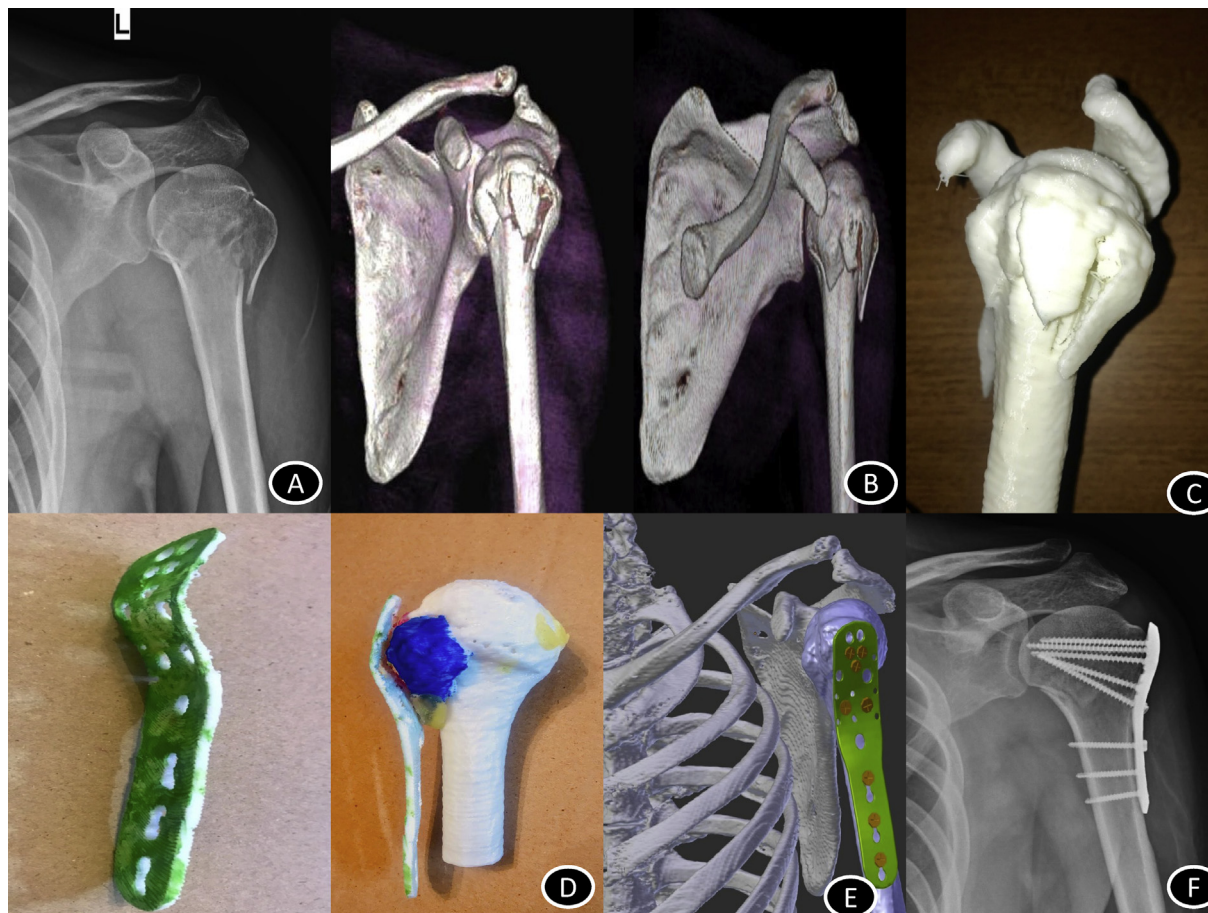


Fig. 3. Virtual preoperative planning of a comminuted proximal humeral fracture. (A) Preoperative X-ray; (B) Virtual 3D model designed from DICOM images; (C) 3D model printed with a 3D printer; (D) Pre-contoured plate template printed; (E) Pre-contoured plate designed; (F) Postoperative X-ray.

Table 1
Surgeon's responses to the questionnaire for 3D printing.

Case	Rationale of using 3D printing	Surgical duration reduced	Change of surgical plan	Improved inventory management	Application of 3D printing feasible	Postop X-ray as planned	Future recommendation of 3D printing	Score
Acetabular fracture	Precontoured plates	+	–	+	+	+	+	5
Nonunion distal tibia	Precontoured plates	+	+	+	+	+	+	6
Tibial plateau fracture	Precontoured plates	+	–	–	+	+	+	4
Cervical spine fracture	Jig designed for pedicle screw placement	–	–	+	–	+	+	3
Carpometacarpal fracture dislocation	Virtual preoperative planning	–	+	+	+	+	+	5
Malunited fracture acetabulum	Jig designed for cup placement	–	–	+	–	+	+	3
Shoulder fracture dislocation	Virtual preoperative planning	+	–	+	+	+	+	5
Intra-articular elbow fracture	Virtual preoperative planning	+	–	–	+	+	+	4
Post traumatic elbow deformity	Virtual preoperative planning	+	+	–	+	+	+	5
Distal radius fracture	Virtual preoperative planning	+	–	–	+	+	+	4
Post traumatic knee deformity	Virtual preoperative planning	+	–	–	+	+	+	4
Femoral head fracture	Virtual preoperative planning	+	+	+	+	+	+	6
Total								4.5

“+” means yes and “–” means no.

learning of medical students and young orthopedic surgeons about anatomical aspect and intraoperative technique for fracture reduction and fixation of complex trauma cases.

We had some limitations in this study, including it being an observational study which lacked a control group and included heterogeneous cases. A comparative study is warranted to objectify the differences and further validate the usefulness of these techniques. Like any other skill, VPP and 3DP also have a learning curve.

Two surgeon's team involved in this study mentioned that the initial time taken during VPP and 3DP was between 3 and 4 h which was more than expected but after few initial cases, the time taken during this process was reduced to 15–20 min only. Initial setup cost for installing a 3D printer was high, starting from 20,000 INR, varying with different vendors but then for each case, it was reduced to only 100 to 500 INR depending on model size, once the surgical team acquired their 3D printer and surgical planning

software. Various software for converting DICOM data into the virtual 3D model is also available free of cost.

Presently, the use of 3DP is in a primitive stage in the field of trauma and orthopedic surgery, due to a lack of sufficient knowledge, additional costs involved and an associated learning curve. We believe that the time has now arrived when we need to become more tech-savvy and learn the applications of VPP and 3DP to deliver optimal care to our patients, with VPP to be considered as the software and the 3DP as the hardware part of it.¹⁸ Although the use of VPP and 3DP is limited for the management of complex trauma cases, shortly these would become a routine and likely to have a significant impact on the practices of orthopedic and trauma surgeons, as this technology is highly cost-effective and offer several distinct advantages, as follows.

- (1) Enhance the understanding of a surgeon about the pathoanatomy of a complicated fracture
- (2) Help in the training of the surgeons in complicated and challenging surgical areas like pelvi-acetabular trauma, intra-articular fractures and spinal surgery
- (3) Preoperative review of the 3D model allows the surgeon to
 - a) do preoperative planning, surgical rehearsal and simulation
 - b) anticipate intraoperative difficulties
 - c) select optimal surgical approach
 - d) plan implant selection and placement
 - e) visualize screw trajectory
 - f) access the need for special equipment
- (4) Intraoperative review of the sterilized 3-D printed model is possible
- (5) Help in the evaluation of restoration of individual anatomy after surgery
- (6) May help in making a precise anatomical diagnosis, where it is not otherwise obvious, and in planning subsequent management
- (7) Allow intraoperative referencing and navigation
- (8) Reduce operating time and blood loss
- (9) Offer better surgical accuracy

Our belief is also supported by the current literature, where it has been noticed that there is a significant increase in the interest in 3DP in the trauma and orthopedic surgery, as is evident by an increasing trend in research and publications in this field in the recent years.^{19,20} Looking at the latest publication trends, we are enthusiastic that it holds the key to future in orthopedics and trauma cases.

To sum up, virtual preoperative planning and 3DP aid in efficient management of complex orthopaedic trauma. This help not only in the better understanding of fracture pathoanatomy and subsequent planning but also in designing patient-specific templates or jigs for accurate placement of implants. Ultimately, VPP and 3DP reduce surgical duration and invasiveness and deliver better surgical outcomes. Although, these also have an initial learning curve, with more experience of using these techniques, the time and efforts required become much lesser than initial cases. With improving technologies and advancements, the utility of these techniques is going to increase.

Funding

Nil.

Ethical statement

Informed consent was obtained from every individual participants included in the study.

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Conflicts of interest

All the authors declare they have no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cjtee.2019.07.006>.

References

1. Cai H. Application of 3D printing in orthopedics: status quo and opportunities in China. *Ann Transl Med.* 2015;3(Suppl 1):S12. <https://doi.org/10.3978/j.issn.2305-5839.2015.01.38>.
2. Lal H, Patralekh MK. 3D printing and its applications in orthopaedic trauma: a technological marvel. *J Clin Orthop Trauma.* 2018;9:260–268. <https://doi.org/10.1016/j.jcot.2018.07.022>.
3. Vaish A, Vaish R. 3D printing and its applications in orthopedics. *J Clin Orthop Trauma.* 2018;9(Suppl. 1):S74–S75. <https://doi.org/10.1016/j.jcot.2018.02.003>.
4. Dai KR, Yan MN, Zhu ZA, et al. Computer-aided custom-made hemipelvic prosthesis used in extensive pelvic lesions. *J Arthroplast.* 2007;22:981–986.
5. Li H, Wang L, Mao Y, et al. Revision of complex acetabular defects using cages with the aid of rapid prototyping. *J Arthroplast.* 2013;28:1770–1775. <https://doi.org/10.1016/j.arth.2012.12.019>.
6. Lu S, Xu YQ, Chen GP, et al. Efficacy and accuracy of a novel rapid prototyping drill template for cervical pedicle screw placement. *Comput Aided Surg.* 2011;16:240–248. <https://doi.org/10.3109/10929088.2011.605173>.
7. Lu S, Xu YQ, Lu WW, et al. A novel patient-specific navigational template for cervical pedicle screw placement. *Spine (Phila Pa 1976).* 2009;34:E959–E966. <https://doi.org/10.1097/BRS.0b013e3181c09985>.
8. Maini L, Verma T, Sharma A, et al. Evaluation of accuracy of virtual surgical planning for patient specific pre-contoured plate in acetabular fracture fixation. *Arch Orthop Trauma Surg.* 2018;138:495–504. <https://doi.org/10.1007/s00402-018-2868-2>.
9. Ma XY, Feng YF, Ma ZS, et al. The promotion of osteointegration under diabetic conditions using chitosan/hydroxyapatite composite coating on porous titanium surfaces. *Biomaterials.* 2014;35:7259–7270. <https://doi.org/10.1016/j.biomaterials.2014.05.028>.
10. Li X, Ma XY, Feng YF, et al. Osseointegration of chitosan coated porous titanium alloy implant by reactive oxygen species-mediated activation of the PI3K/AKT pathway under diabetic conditions. *Biomaterials.* 2015;36:44–54. <https://doi.org/10.1016/j.biomaterials.2014.09.012>.
11. Lo NN, Goh PS, Khong KS. Radiation dosage from use of the image intensifier in orthopaedic surgery. *Singap Med J.* 1996;37:69–71.
12. Lewinnek GE, Lewis JL, Tarr R, et al. Dislocations after total hip-replacement arthroplasties. *J Bone Joint Surg Am.* 1978;60:217–220.
13. Robertson DD, Sutherland CJ, Lopes T, et al. Preoperative description of severe acetabular defects caused by failed total hip replacement. *J Comput Assist Tomogr.* 1998;22:444–449.
14. Munjal S, Leopold SS, Kornreich D, et al. CT-generated 3- dimensional models for complex acetabular reconstruction. *J Arthroplast.* 2000;15:644–653.
15. Yu AW, Duncan JM, Daurka JS, et al. A feasibility study into the use of three-dimensional printer modelling in acetabular fracture surgery. *Adv Orthop.* 2015;617046. <https://doi.org/10.1155/2015/617046>.
16. Wong KC, Kumta SM, Geel NV, et al. One-step reconstruction with a 3Dprinted, biomechanically evaluated custom implant after complex pelvic tumor resection. *Comput Aided Surg.* 2015;20:14–23. <https://doi.org/10.3109/10929088.2015.1076039>.
17. Tetsworth KD, Mettys T, Tamer M. Overview of emerging technology in orthopedic surgery: what is the value in 3D modeling and printing? *Tech Orthop.* 2016;31:143–152. <https://doi.org/10.1097/BTO.0000000000000187>.
18. Maini L, Vaishya R, Lal H. Will 3D printing take away surgical planning from doctors? *J Clin Orthop Trauma.* 2018;9:193. <https://doi.org/10.1016/j.jcot.2018.06.013>.
19. Vaishya R, Patralekh M, Vaish A, et al. Publication trends and knowledge mapping in 3D printing in orthopaedic. *J Clin Orthop Trauma.* 2018;9:194–201. <https://doi.org/10.1016/j.jcot.2018.07.006>.
20. Bagaria V, Chaudhary K. A paradigm shift in surgical planning and simulation using 3Dgraphy: experience of first 50 surgeries done using 3D-printed bio-models. *Injury.* 2017;48:2501–2508. <https://doi.org/10.1016/j.injury.2017.08.058>.