Indian Journal of Surgical Oncology
https://doi.org/10.1007/s13193-025-02205-y

ORIGINAL ARTICLE

3D Printing in Orthopedic Oncology — Workflow and Outcomes of 59 Cases

Amar Kamat[1] · **Pramod Chinder**[1] · **Anto Gopurathingal**[1] · **Suraj Hindiskere**[1]

Received: 4 December 2024 / Accepted: 8 January 2025

Abstract

3D printing has become an integral part of orthopedic oncology. Yet the penetration of this technology is very low owing to a lack of understanding of workflow or early failure due to variables that were not considered during the planning stage. To report preliminary results and pitfalls and describe a workflow based on our experience. This is a descriptive, observation study of 59 cases done by assistance of 3D printing from March 2016 to September 2021. An account of basic workflow, tips, and pitfalls in planning and institutional protocols is described. We categorized and analyzed cases based on clinical parameters such as resection margin, operation time, and blood loss. Several cases that had planning pitfalls also have been identified. Resection via 3D-printed jigs resulted in an average resection margin of 1.2 mm. Operating time was lesser by an average of 25 min (p-value 0.049) for 3D-printed implants, though there was no significant difference in blood loss (p-value 0.24). 3D-planned aids had to be abandoned in three cases due to unforeseen intra-operative challenges. In lower limb 3D-printed plates, the average time to union was 4 months. There were no cases of nonunion or delayed union. Fluoroscopy exposure was reduced significantly. 3D printing-assisted resection keeps resection to a minimum by providing adequate oncological clearance. It also helps reduce operating time and fluoroscopy exposure.

Keywords 3D printing · Orthopedic oncology · Workflow and plan

Introduction

Once "avant-garde" in the field of healthcare, 3-dimensional printing (3DP) has evolved from cutting-edge technology to a basic need in the management of several intricate conditions in the field of surgery. 3DP helps in simplifying the byzantine cases in the field of surgery, thereby making mountains seem smaller for the reconstructive surgeons operating in complex territories. The literature is not scanty on why 3DP should be in the kitty bag of every reconstructive surgeon fighting the good fight. However, the penetration of this much-needed tool is very low in practice because of the perplexity that the technology brings to surgeons in general. The aim of this paper is to disentangle and simplify the entire process of using 3D printing so that orthopedic onco-surgeons can explore the full potential of this novel technology. We will present a practical workflow, tips and tricks, and technical pearls for using 3DP technology for orthopedic oncology patients based on our experience of 59 cases spanning a decade.

Spectrum of Application

3D Anatomy Models

Complex surgeries are mostly termed so because of the complex anatomy of bone and soft tissue in the area. A large

Clinical Message A documented workflow and plan with coordination with an engineer specializing in 3D printing is a must to obtain satisfactory oncological outcomes.

✉ Amar Kamat
amarkamat2910@gmail.com

Pramod Chinder
hcgbonecancer@gmail.com

Anto Gopurathingal
aantoh@gmail.com

Suraj Hindiskere
suraj.ortho@gmail.com

[1] Department of Orthopedic Oncology, HCG Hospital, Bangalore 540027, India

pelvic tumor (Fig. 1) or spine chordoma is a challenge to visualize as a whole even from the most advanced scans and 3D reconstruction models on screen. Many times a 3D reconstructed bone model superimposed with a tumor, sometimes even the vascular structures (Fig. 2), gives an overview of the challenge and brings out more efficient and confident dissections [1].

In our experience, these reduce the operative timing as the surgeon is well aware of the obscure anatomy a large tumor has caused. The tortuous turns of the neuro-vascular structures may be difficult to keep track of in relation to the anatomy even on contrast-enhanced scans [2].

Tiptoeing around a huge tumor anticipating neuro-vascular structures can consume a lot of operating time.

From a patient's perspective, seeing a 3D model can enhance their understanding of the procedure [3]. We have found in our practice that patients become well-versed with the challenges the surgeon is going to face intra-operatively, and hence are more empathetic to a postoperative outcome or a complication.

Patient-Specific Cutting Guides

Taking cuts in a bone in orthopedic oncology is of utmost importance. While attempting to cut lesser bone, the margin clearance can never be compromised. Even though the teaching is to err on the bone stock and not in the margin clearance, the advent of technology gives us no excuse to err here or there. The classical approach of taking bone cuts by using the ruler that was measured on magnetic resonance imaging (MRI) scans in an uneven bone is just a recipe for disaster. The jigs give the surgeon the confidence of margin clearance by resecting the least amount of bone (Fig. 3).

Intra-operative reconciliation of bone cut using image intensification does not account for marrow edema which might be a reactive zone of a malignant tumor. A repeat frozen section on a revised bone cut increases the operative time by at least 20 min among other drawbacks that haunt a frozen section confirmation [4].

Patient-specific cutting guides have been employed by us for bone cuts in complex territories such as the pelvis

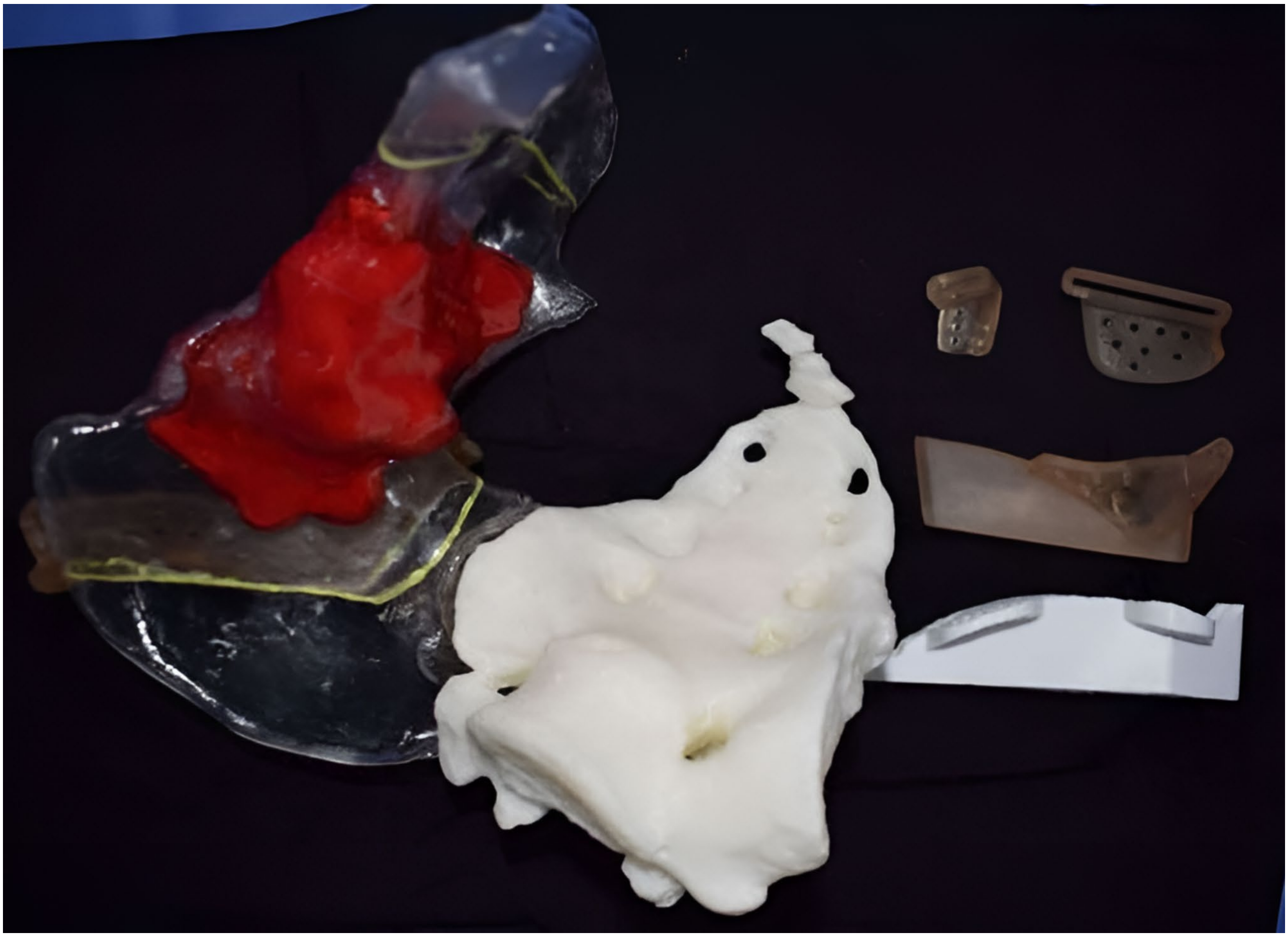

Fig. 1 3D-printed model of a large pelvic tumor

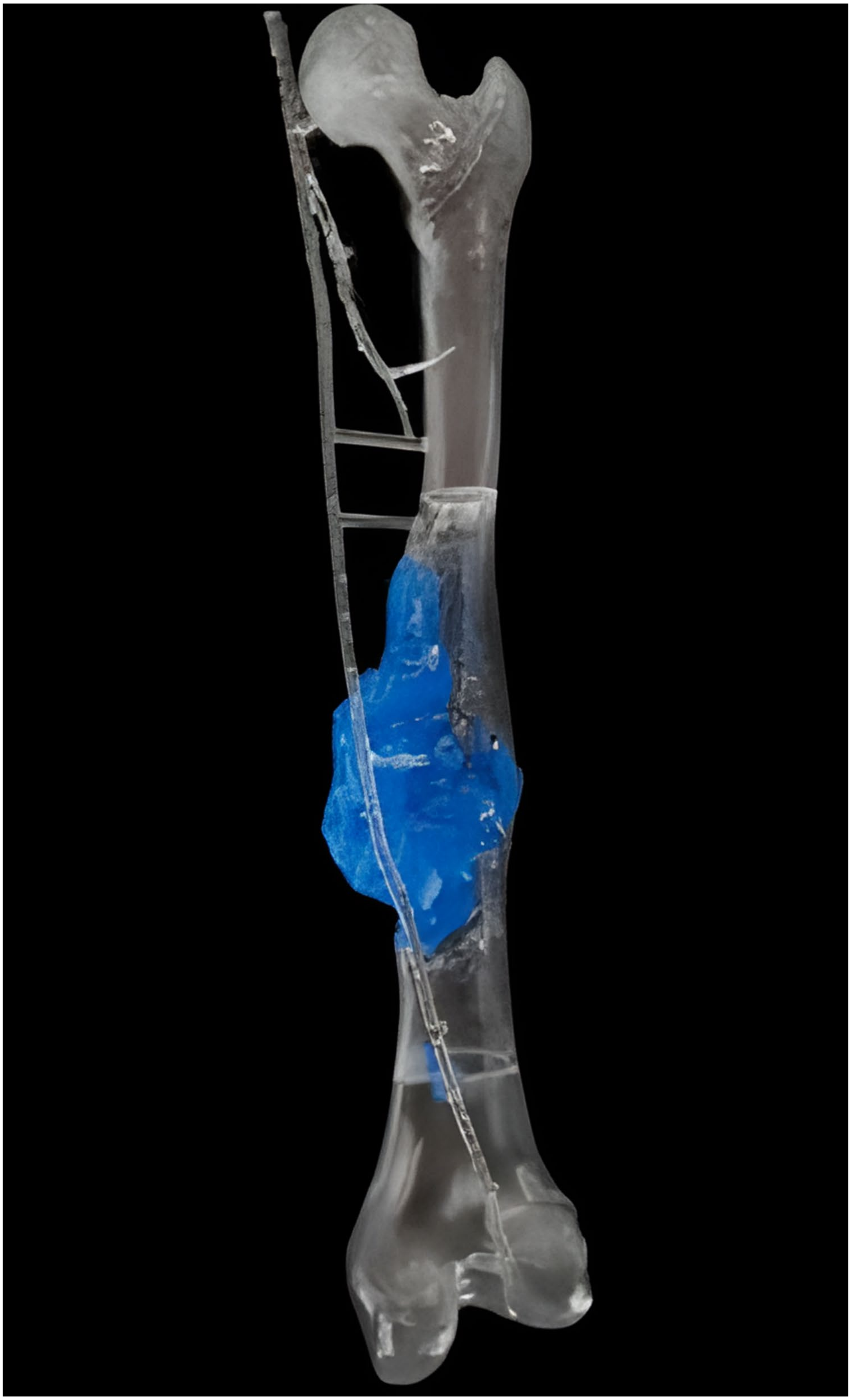

Fig. 2 A shaft of femur osteosarcoma showing relation to femoral artery and branches to the tumor. This branch was embolized preoperatively. Bone cuts for ECRT are planned pre-operatively on the model keeping adequate clearance

(Fig. 4) and spine. In pelvic tumor surgery, the complexity of the pelvic anatomy makes a bony resection with the particular desired orientation for accurate fitting of the custom prosthesis a challenge. In such areas, the depth-controlled jigs that have been calibrated to the saw we use have limited our cuts to just the bone and thereby protect the vital

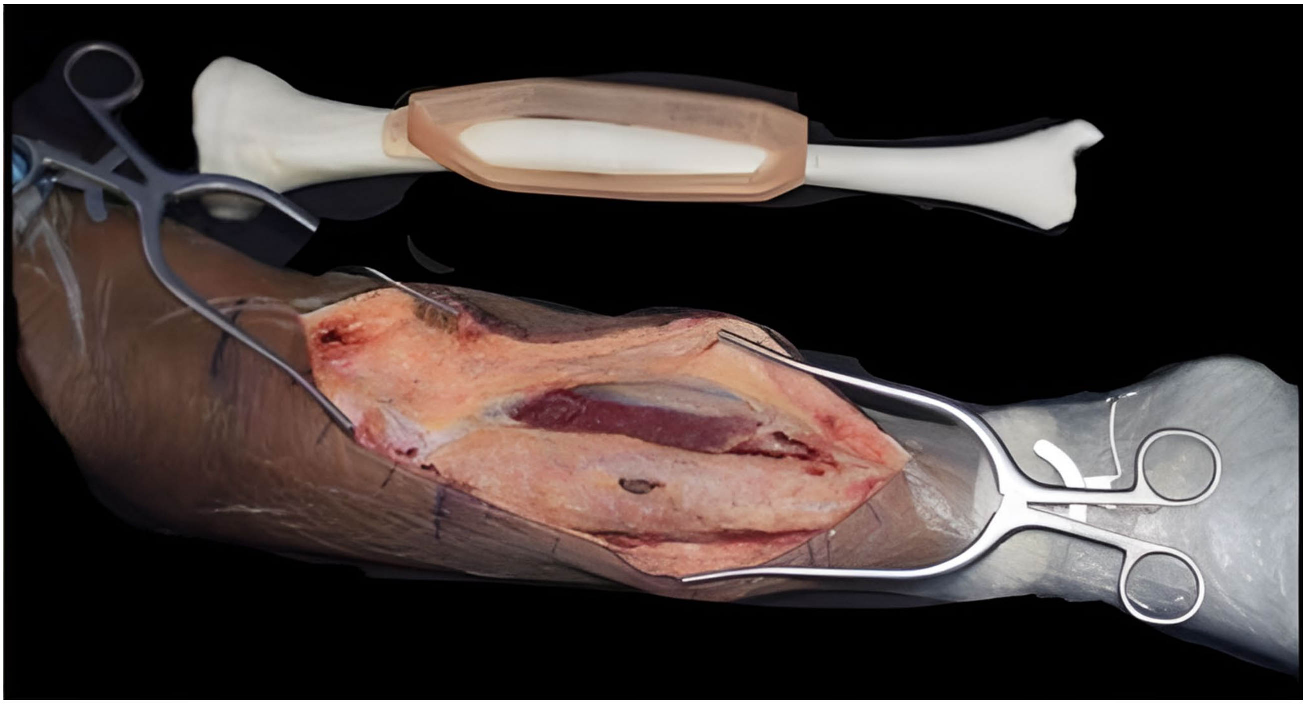

Fig. 3 Shaft of tibia OFD resected with tailor made cutting guide that could be secured with k wires to preserve maximum bone

structures underneath. Injuries to the rectum, genitourinary, and neuro-vascular during sacral chordoma excision have been reported [5]. Jigs have also given us the confidence to cut the bone, without fretting under the uni-dimensional image intensifier guidance as in the case of a pelvic resection, where we try to save the pelvic ring or leave behind adequate bone stock for prosthetic reconstruction. A high degree of accuracy in resection of the bone is of utmost importance, given that the prosthesis is made to 1:1 dimensions. Any errors in bone cuts may eliminate treatment options or may result in inadequate resection margins. Cartiaux et al. (2008) demonstrated that four experienced surgeons could achieve a 10-mm resection margin, with 5-mm tolerance, on pelvic sawbones in only half of the resections [6]. In junta-articular lesions, the cutting guides may be instrumental in saving the joint or the physis.

3D-Printed Implants

Once recycled autograft was increasingly used in limb salvage surgery, the need of the hour were patient-specific implants. The tumor resection margin dictated where screws can be put in to refix the bone that had undergone extra-corporeal radiation therapy (ECRT) or pedicled liquid nitrogen freezing. Standard plate designs used for trauma were largely useless in this cohort of patients. Availability of pediatric plates in all sizes was a difficulty. This is a glaring problem because a large portion of the recycled autograft surgeries was done in the pediatric age group (Fig. 5A–C).

Custom-made plates were printed in titanium with provision for locking screws. Such plates could be printed as per the profile, length, number of screws, direction of screws, and deformity in the bone. Locking screws with bone-specific lengths as measured on MRI were printed and tried on a 3D-printed model of the same patient preoperatively. This ensured there were fewer errors intraoperatively and the procedure was a lot quicker.

3D-Printed Prosthesis

Standard endoprosthesis that is readily available in the market covers most of the mega-reconstruction needs of a tumor surgeon. The prostheses of extremities are rarely printed [7]. In our practice, massive endoprosthesis printing was done for pelvic and shoulder girdle tumors (Fig. 6). The deficit created by the resection was planned in advance and the prosthesis was designed with computer-assisted drawing.

Point of fixation was planned with screws, plate-screw, posts, cement, and interlocking bolts. The prosthesis was coated with hydroxyapatite for integration to host bone or allograft. Provision was added for the attachment of muscles, tendons, and ligaments.

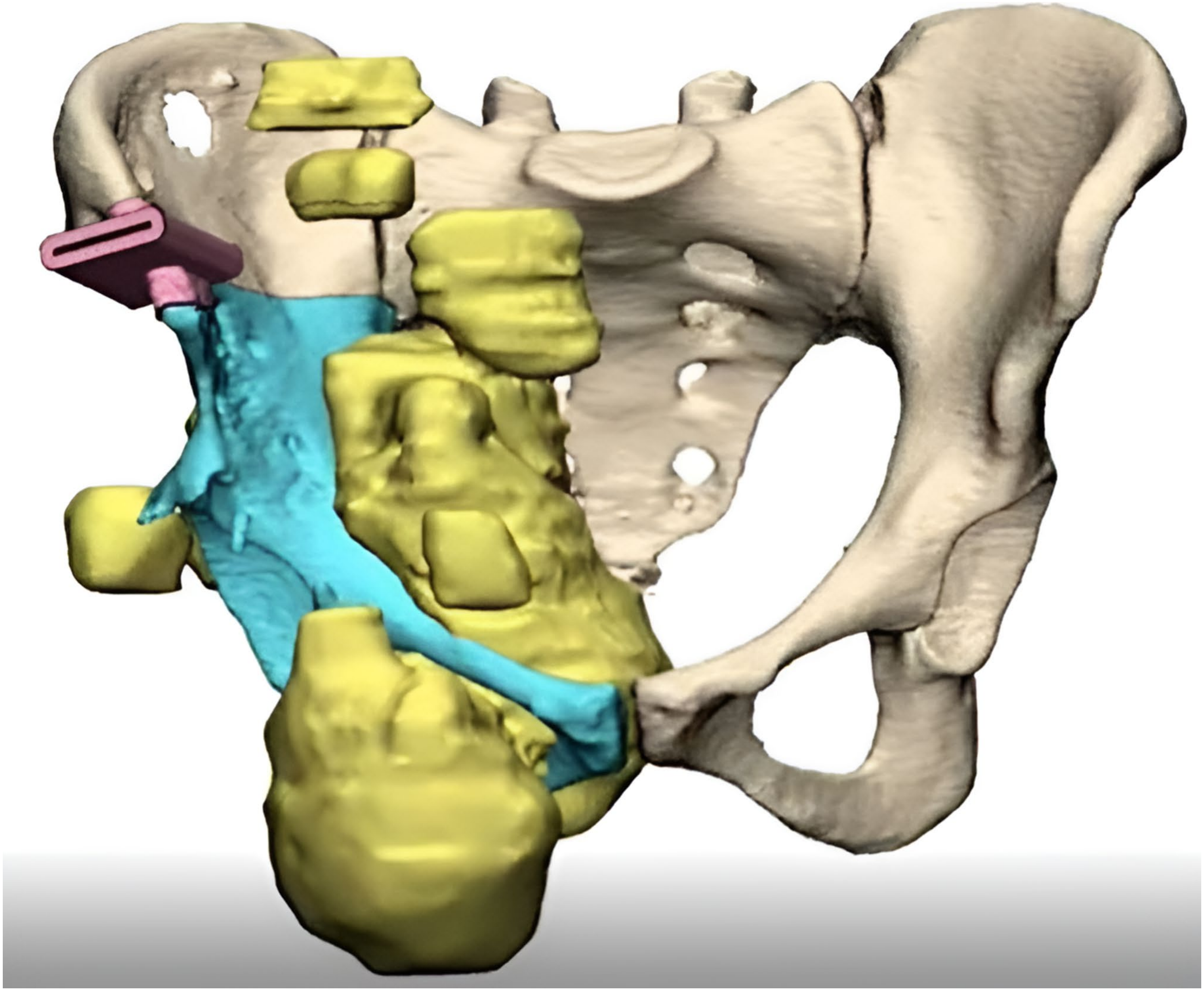

Fig. 4 Jigs used for complex pelvic resections

Methods

This paper has been written based on our experience as a comprehensive and exclusive tertiary cancer center in India. The Department of Orthopedic Oncology at our center sees over 1100 patients and operates close to 150 patients annually. Our practice with respect to 3D printing has gone through abundant transitions over the years as the costs of technology changed. We present a descriptive, observational, retrospective, and mono-centric study of 59 cases assisted by 3DP technology between 2016 and 2021 (Fig. 7).

Finding the Appropriate Industrial Support

There is no dearth of companies that offer 3D printing support across the world. Delay or inexperience can erode away valuable waiting periods for a cancer patient and cause delays which can result in less satisfactory outcomes. A team should be evaluated in the following key steps.

Segmentation

This is a process in which the bone and tumor or structures in question, such as nerve and vessels, are delineated from the CT/MRI scans. These can be done on computer-aided design (CAD) software. The process of segmentation has evolved from being completely manual to semi-automatic to fully automatic. Manual segmentation will require a step-by-step drawing of the tumor and bone in every slice. It is a time-consuming process. Semi-automated and fully automated systems on the other hand are a much faster process where an image is divided into regions with similar properties such as gray level, color, texture, brightness, and contrast. A fully automated system has a high failure rate

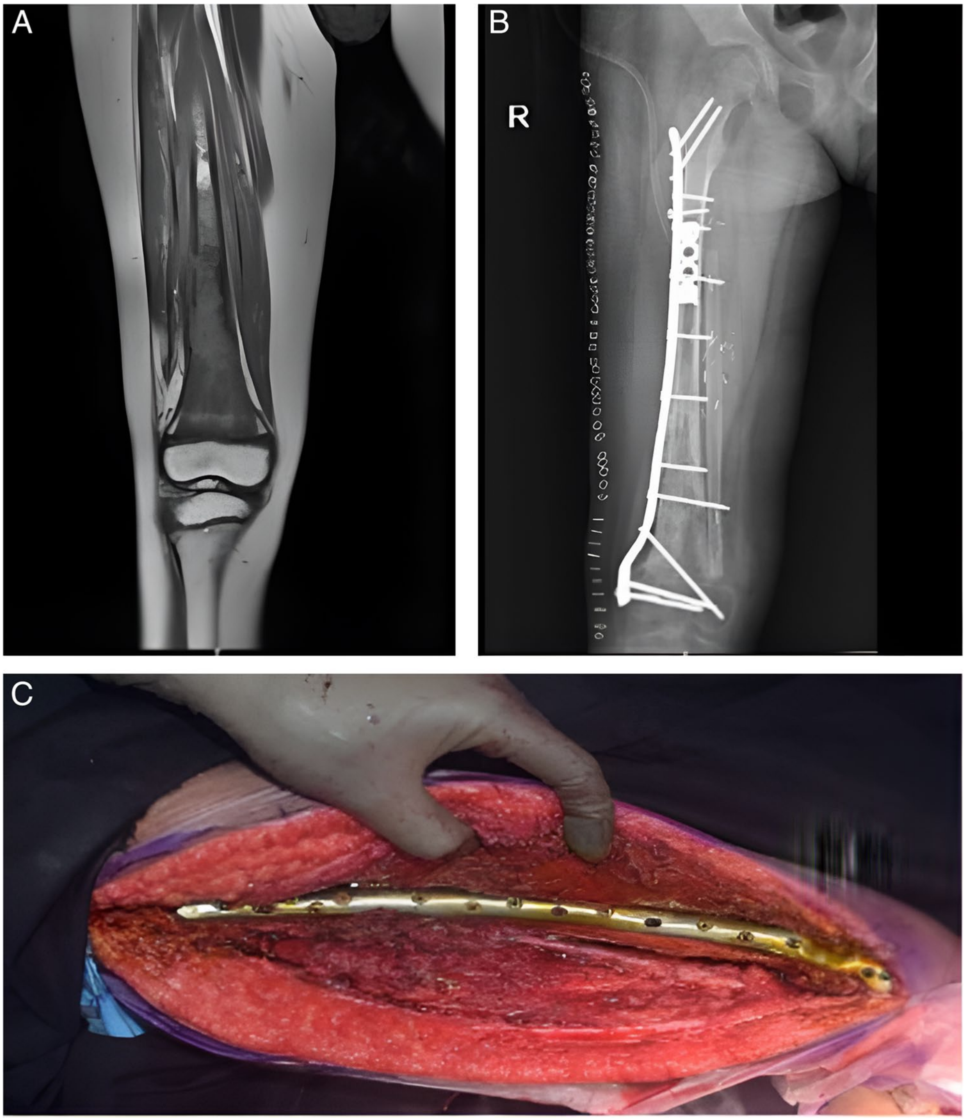

Fig. 5 **A**–**C** Distal femur OS with involvement of physis as well. A cut distal to physis was the only way to save the joint. Here the joint was saved due to a reliable distal femur plate with custom-designed screw direction and number. Plate is well contoured to the pediatric femur and is holding recycled autograft and vascularized fibula

owing to the complex nature of the tumor. The output of the segmentation algorithm is affected due to imaging issues like partial volume effect, presence of artifacts, intensity inhomogeneity, closeness in gray level of different soft tissue, etc. [8]. We follow a semi-automated system in which the borders of a software-segmented tumor or anatomical structure are revised by engineers and radiologists in conjunction to get maximum accuracy. In summary, it is imperative that the biomedical engineers that one associates with have a semi-automated segmentation proficiency. In such a system, segmentation would not take more than an hour.

Printing

It is important to have an idea of what printing technique the industry that we employ is using. There are four types of printing techniques that are most common. Appropriate technique is used as per our requirement.

Stereolithography (SLA) printing can be used to generate bone models. It works by melting resins hence giving a better finish to the models. Fused deposition modelling (FDM) uses plastic polymers (polylactic acid (PLA), acrylonitrile butadiene styrene (ABS)). It prints by layered deposition and so the overall

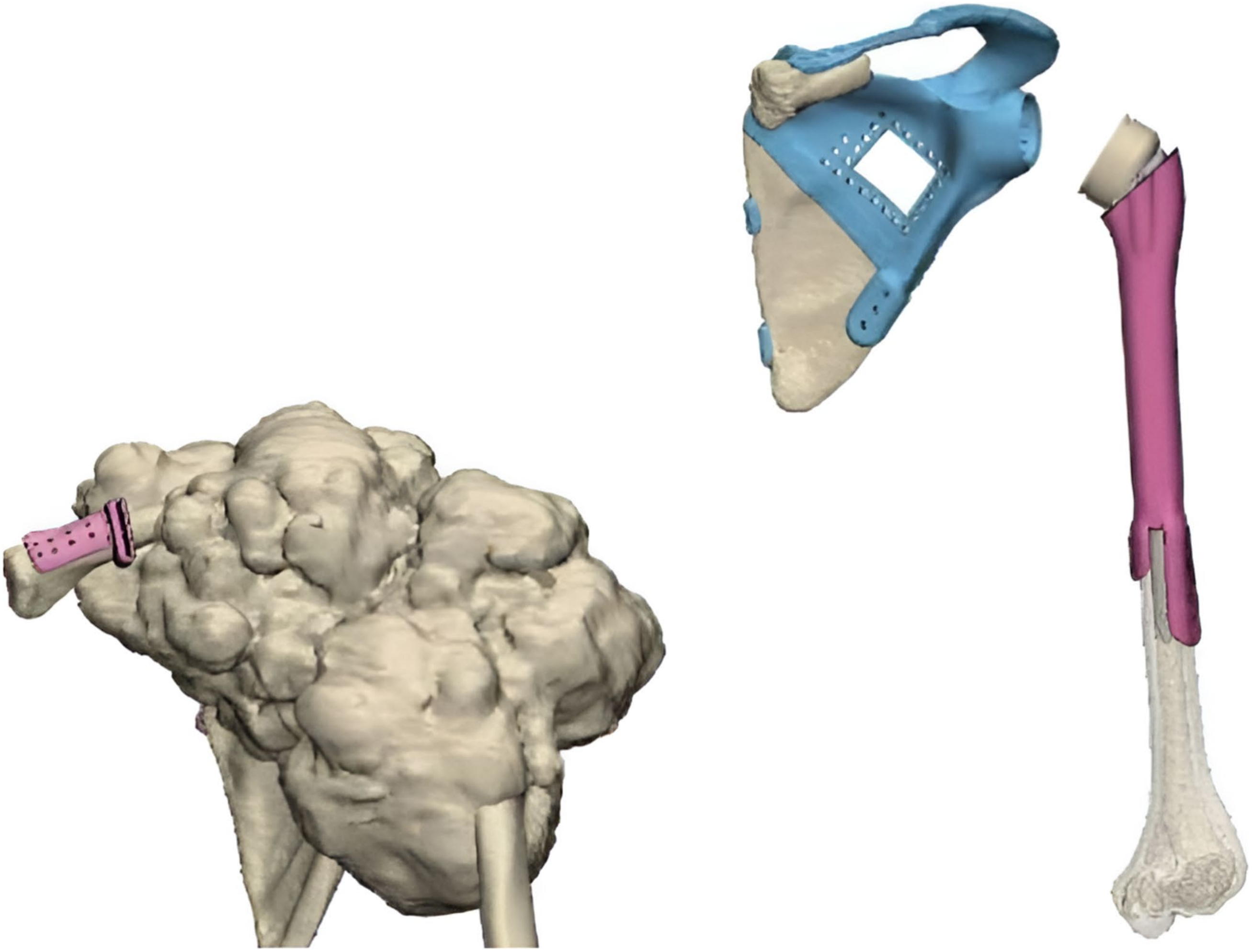

Fig. 6 Shoulder chondrosarcoma which could be managed by limb salvage because of this custom-made 3D-printed prosthesis. A reverse shoulder prosthesis was implanted into this printed prosthesis for the articulation

finish of the surface is of lesser quality but it is cost-effective owing to the comparatively cheaper price of the printer and raw material compared to SLA; and hence, these are most commonly used by non-professionals. Laser sintering allows the use of metals and other materials for printing. Selective laser sintering (SLS) can be used for non-metal printing purposes. Direct metal laser sintering (DMLS) is suited for metal printing and for obvious reasons is the most expensive technique to execute. These are mostly used in industrial-grade printing. Such printers are used for prosthesis and implant printing.

Preoperative Planning

Bone

When measuring bone cuts, we have to keep in mind that there is a chance for the measurement to be under-presented in CT/MRI. Hence when planning a bone resection we tend to take an extra centimeter for a margin more than what is measured in the MRI/CT. 1:1 models can be smaller than the actual model.

Soft Tissue

Soft tissue obstruction to seating an implant can happen in the following situations, and hence has to be carefully checked for before planning a jig or implant:

(a) Radiation-induced soft tissue contracture.
(b) In delayed reconstruction, long-standing deformity may have caused ligamentous laxity/contracture.
(c) Soft tissue bulk at a bony site may bar snug fit of the jig onto the bony prominence. Hence another site of jig fixation may have to be planned.

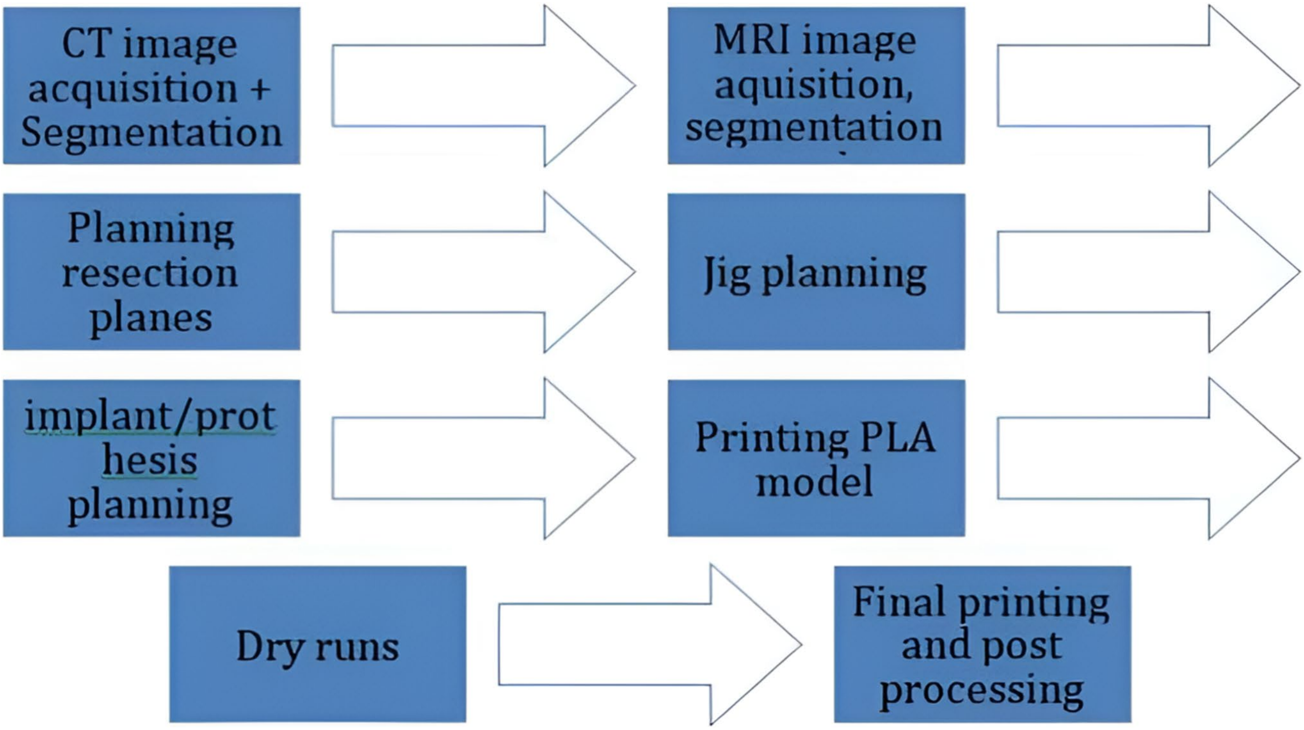

Fig. 7 Workflow for 3D printing

Neurovascular Structures

Neurovascular structures can get grossly displaced after the removal of a large tumor. These may have to be released or reconstructed to ensure adequate seating of the implant or prosthesis.

Communications to the Radiology Desk CT Image Acquisition

This protocol describes the guidelines followed by us for a CT scan for ordering titanium 3D-printed patient-specific implants, plates, guides, and anatomic models.

General Considerations

(a) Cone-beam computed tomography (CBCT) scans are not accepted for patient-specific implants.
(b) Patient-specific implants will be designed to fit the patient's anatomy at the time of the CT scan.
(c) Changes in the patient's anatomy occurring after the CT scan, as well as the use of the device after such changes, may result in a suboptimal fit of the device or implant. Scans must be less than 2 months old. We use the following scan parameters or the closest approximation possible.

Preparation of the Patient for Scan

(a) Remove any non-fixed metal prostheses or jewelry.
(b) Non-metal dentures may be worn during the scan.
(c) Make the patient comfortable and instruct him not to move during the procedure.
(d) Normal breathing is acceptable but any other movement, such as tilting and/or turning the head, can cause motion artifacts that compromise the reconstructed images requiring the patient to be rescanned.
(e) Stabilize the relationship of the jaws during the scan. The patient is preferably scanned with a very thin bite wafer that does not influence the facial soft tissues.

Patient Positioning

(a) Place the patient supine on the scanner table and move the patient into the gantry, headfirst.
(b) Minimize the artifacts caused by metallic dental restorations or orthodontic brackets by aligning the patient's.
(c) Occlusal plane as much as possible with the axial slices.
(d) Do not deform the soft tissue.

CT Scanning Instructions

(a) Images scanned under a gantry tilt and oblique or reformatted images negatively influence the accuracy, it is recommended only primary axial images.
(b) All slices must have the same field of view, reconstruction center, and table height.
(c) Scan with the same slice spacing, less than or equal to the slice thickness.

Reconstruction of the Images CT

Use these listed CT scan parameters for image reconstruction or as the closest approximation possible:

(a) Gantry tilt/oblique angle 0°
(b) Matrix 512 × 512
(c) Slice thickness maximum 1.0 mm
(d) Feed per rotation maximum 1.0 mm
(e) Reconstructed slice increment maximum 1.0 mm.
(f) Pixel size or pixel spacing must be less than 0.5 mm.

Accepted media: Standard Digital Imaging and Communications in Medicine (DICOM) format—CD or DVD.

MRI Acquisition Protocol

This protocol describes the guidelines used by us for an MRI scan that is taken for the purpose of ordering a 3D-printed anatomical model and implants. This protocol is preferably transferred to the radiology department, together with the scan order. Using this scanning protocol will result in a more accurate model.

Preparation of the Patient

(a) Remove any non-fixed metal dentures or prostheses, in addition to any jewelry that might interfere with the region to be scanned. Place the patient supine on the scanner table and move the patient into the gantry, headfirst.
(b) Make the patient comfortable and instruct him not to move during the procedure. Normal breathing is acceptable, but any other movement, such as tilting and turning the head, can cause motion artifacts that com-

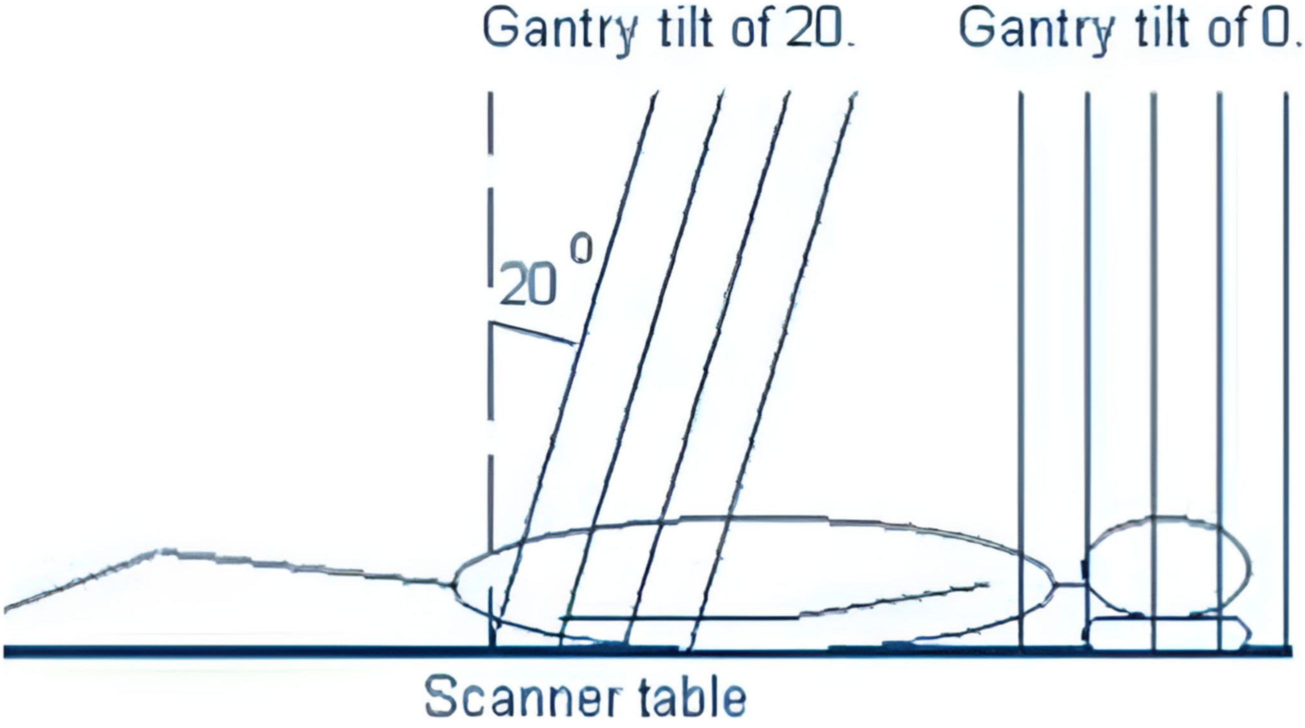

Fig. 8 Gantry tilt angle

promise the reformatted images, requiring the patient to be rescanned.

Aligning the Patient

(a) It is very important to know whether a patient has been scanned with a gantry tilt angulation other than 01 or not. Although the software has been adapted to support data scanned with gantry tilt, interpolations and 3D representation will have an inferior quality due to the gantry tilt. It is therefore advised not to use a gantry tilt.
(b) If the only option is to use a gantry tilt, please indicate the direction of angulation when the data is sent (Fig. 8).
(c) Align the patient in a way that prevents as many artifacts as possible in the resulting images.
(d) Use the head holder with sponges to stabilize the position. If you cannot orient the head properly in the head holder, use the tabletop. In either case, strap the head securely to prohibit motion. Stabilize the relationship of the jaws during the scan. The patient is preferably scanned with the jaws slightly open if available; you can use a bite block. This will reduce the risk of artifacts from the opposing jaw, disturbing the images of the jaw of interest. Also, this will make it possible to isolate the occlusal plane from the images.
(e) You can take a lateral alignment image (called a Localiser, Scout view, topogram, Scanogram, Pilot, or Sunview depending on the MR manufacturer) to verify the correct patient positioning.

Scanning Instructions

(a) Set the table height so that the area that needs to be scanned is centered in the scan field.
(b) All slices must have the same field of view, the same reconstruction center, and the same table height.
(c) Not overlapping the axial slices can reduce the quality of the reformatted images.
(d) Scan all slices of the study in the same direction.
(e) Scan with the same slice spacing; the slice spacing must be less than or equal to the slice thickness.
(f) The slice thickness should preferably not be larger than 1 mm.
(g) Scan direction: axial or sagittal matrix (preferred): 512×512, slice thickness (preferred): less than 1 mm (Fig. 9)

Image Reconstruction

Use a proper image reconstruction algorithm to get sharp reformatted images where you can locate internal structures such as the alveolar nerve and for bony anatomy use bone or high-resolution algorithm.

Fig. 9 Scanning technique options

Scanning Technique options

	Flip Angle	TR (ms)	Echo train	TE (ms)	Slice (mm)	FOV (cm)	Voxel (mm^3)
3D-FEMR** (Preferred)	20	6.7	1	2	1.5	~14	~0.75
3D T2-SPGR	40	50	1	5	1.5	~14	~0.75
2D T2-SPGR	90	2800	6	31	2	~14	~0.75

Table 1 Patient characteristics

Category	Variable	
Patients	Total patients	59
	Anatomy models printed	59
	Patients with jigs planned	25
	Patients with 3D-printed implants used	16
	Patients with 3D-printed prosthesis planned	6
	Patients undergoing planned procedures	56
	Abandoned cases	3 (1 pelvic prosthesis, 1 tibial resection with jig, 1 distal femur conventional plating)
Tumor characteristics	Resection margin	Average: 23 mm (range 10–38 mm)
Procedure characteristics	Surgical time difference (posterior pelvic cuts using jigs)	Reduced by 35 min (average in 3 cases with jigs vs. 3 cases without jigs)
	Surgical time (femur resections with jigs)	No significant difference
	Blood loss comparison	No significant difference (*p*-value 0.24)
	Time for graft implantation (3D plates)	18 min (vs. 38 min with conventional plates)
	Fluoroscopy usage (conventional plates)	Mean exposure time: 4.09 min (radiation 0.1–0.22 mSv)
Outcomes	Average follow-up	28 months (range 10–36 months)
	Time to union (lower limb, 3D plates)	Average: 4 months (range 3–6 months)
	Complications (3D prostheses)	None (no instability, loosening, or periprosthetic fractures)

Accepted media: Standard DICOM format—CD or DVD.

Communications to the Engineer

(a) The incision area and bony landmarks that can be used for jig positioning or implanting a prosthesis have to be marked out.
(b) Large prostheses should be designed with a lattice structure to bring down the weight of the prosthesis.
(c) For prostheses with large working lengths, an additional screw fixation apart from cementing should be planned.
(d) The length and breadth of the saw used have to be communicated for efficient planning of jigs so that a stop can be planned on the jig to avoid any inadvertent injury to vital structures.
(e) Jigs should be planned with provision for k-wire fixation.

Preoperative Dry Runs

(a) Check for sagittal plane mismatch.
(b) Confirm all screw holes are directed properly
(c) Plan screw length in advance

Results (Table 1)

In total, 59 patients underwent planning and management with 3D printing technology. All patients had an anatomy model printed. Twenty-five patients had jigs planned. Sixteen patients had 3D-printed implants used, and six patients had 3D-printed prostheses planned.

Fifty-six patients underwent the planned procedure. One patient planned for a 3D-printed pelvic prosthesis had to be abandoned intra-operatively after encountering extensive soft tissue contracture in the pelvis from adjuvant radiation. This was not taken into consideration in the preoperative planning. One pediatric patient with osteofibrous dysplasia of the tibia was planned for resection of the segment with 3D-printed jigs. Since the tibialis anterior insertion and thick periosteum were not taken into consideration, the jig would not fit snugly onto the anterior surface of the tibia. The resection had to be carried out under C arm guidance after further exposure.

Another patient planning for a 3D-printed plate in a case of pedicled frozen distal femur osteosarcoma had to be done using conventional plates because of a logistical delay in planning and printing. The conventional plate was ill-fitting as the plate was proud of the greater trochanter.

All cases had R-0 resection with the average resection margin being 23 mm (range 10–38 mm). The frozen section was done intra-operatively for all patients.

In three cases where jigs were used for posterior bone cut for type 1/4 resections in pelvis the surgical time by 35 min on average in the three cases compared to three other similar cases where jigs were not used. Additional time was required to do more exposure and to place careful cuts so as to not injure the structures behind. In eight cases of femur resections, the time difference did not reach significance.

There was no significant difference (p-value 0.24) in average blood loss when compared to similar anatomical sites operated without 3D-printed jigs.

In 12 cases of 3D-printed plates for femur resections followed by recycled autograft [$n=8$] or massive allograft reconstruction [$n=4$], the average time for implantation of the graft + free fibula construct was 18 min whereas using conventional plates average time was 38 min. Fluoroscopy was used only for the final screening of the implant fixation. In the case of conventional plating, the mean exposure time was 4.09 min, and 0.1–0.22 mSv radiation was emitted [9]. The average follow-up is 28 months (range of 10–36 months). The average time to union in cases operated with 3D-printed plate constructed in the lower limb was 4 months (range of 3 – 6 months). There was no instability, loosening, or peri-prosthetic fracture in this series of cases with 3D-printed prostheses.

Discussion

3D printing aids give the advantage of reducing operating time, reducing the need for frequent fluoroscopy exposure, avoiding implant malpositioning, and decreasing intra-operative blood loss. 3D-printed anatomical models aid the surgeon's 3D orientation of the anatomy which can improve the flow of surgical care. Oncological surgical treatment is a trade-off between adequate margins and function, with the margin being more important. Rough calculations on radiological imaging without proper landmarks to depend on during the surgery make bone resections dangerous.

Resections may vary from going through the tumor increasing the chances of spillage, to resections far away taking more normal bone than required.

3D-printed plates have provided a snug-fitting implant for the pediatric population, where most standard plates are ill-fitting. We have had two patients with delayed union which was managed by bone grafting at 9 months post-op compared to no nonunions in the 3D-printed plate group.

One of the major drawbacks is the time taken for execution. In a case of distal femur osteosarcoma planned for a 3D-printed plate, we had to abandon the planning at a stage because the delay in 3D printing would have adversely affected the patient outcome. The collaboration of the surgeon, radiologist, and engineer becomes another bottleneck in the logistics.

Should you Buy a 3D Printer?

Having a 3D printer in-house requires a very efficient workflow if it has to be economically viable. Challenges are peasant-riddled every step of the way from owning, designing, and printing models and implants.

In India, one might need an International Organization for Standardization (ISO) certification of standardization to own and print medical implants. Most countries need approval from their standardization agencies, Food and Drug Administration (FDA) for the USA, and European Union medical device regulation for all the countries in the EU.

The logistics for owning a 3D printer start with having a space that has sufficient aeration and temperature control. The workforce includes biomedical engineers and designers who specialize in computer-assisted drawing (CAD). Purchasing and stocking the raw material can run into problems particularly if the materials have to be imported. Global goods movement restrictions owing to developments in the geopolitical climate and novel COVID-19 coronavirus infections have been a logistic nightmare for many centers. Technology for designing and printing is fast progressing bringing down the cost and the time taken for processing. Keeping up with the upgradation in the software for designing and hardware of printers can be an expensive affair.

All in all, a large volume of 3D printing requirements, a well-run interdisciplinary workflow between surgeons, radiologists, biomedical engineers, and other technician assistants, and hospital management that is patient and resourceful enough to accept the overwhelming financial investment, are paramount in running a successful in-house 3D printer.

Our current practice has a team of surgeons doing the planning, and a radiologist doing the segmentation. We have liaised with an industrial 3D printing company that does the designing and printing of implants and prostheses. We have recently acquired a low-cost FDM printer that uses PLA polymer as the raw material. It is mainly used for generating bone models for patient education and surgical orientation.

Costing

Costing depends on the requirement of the modality. Basic anatomy models will cost ranging from $100 –200 depending on the size of the specimen being printed. Although the printing of the jig may be an inexpensive affair, the cost involves the time spent by the team on developing and planning the jig. 3D-printed implants such as a titanium plate would cost $800–1000.

Prosthetic printing is an uphill task in terms of planning and printing. A larger amount of raw material will be required and it may take more than 60 h to print. The average cost incurred for a pelvic reconstruction implant was $4000.

Conclusion

3D-printed aids, viz anatomy models, patient-specific cutting guides, implants, and prosthesis, represents a need of the hour in orthopedic oncology especially in pediatric cases and areas of complex anatomy like the pelvis. Even though it is overshadowed by the complexity and time consumed for planning, interdepartmental collaboration, costing, and logistics, it can improve resections, decrease the time of surgery, reduce radiation exposure, and give better long-term outcomes.

Declarations

Ethical Approval Ethical committee approval taken for this study.

Conflict of Interest The authors declare no competing interests.

References

1. Tam MD, Laycock SD, Bell D, Chojnowski A (2012) 3-D printout of a DICOM file to aid surgical planning in a 6 year old patient with a large scapular osteochondroma complicating congenital diaphysealaclasia. J Radiol Case Rep 6:31–37
2. Chang YCC, Ackerstaff E, Tschudi Y et al (2017) Delineation of tumor habitats based on dynamic contrast enhanced MRI. Sci Rep 7:9746. https://doi.org/10.1038/s41598-017-09932-5
3. D'Urso PS, Redmonda MJ (2000) A method for the resection of cranial tumours and skull reconstruction. Br J Neurosurg 14–16. https://doi.org/10.1080/02688690020005581
4. Jaafar H (2006) Intra-operative frozen section consultation: concepts, applications and limitations. Malays J Med Sci 13(1):4–12
5. Varga PP, Szövérfi V, Lazary A (2014) Surgical treatment of primary malignant tumors of the sacrum. Neurol Res 36(6):577–587. https://doi.org/10.1179/1743132814Y.0000000366
6. Cartiaux O, Docquier P, Paul L, Francq BG, Cornu OH, Delloye C, Raucent B, Dehez B, Banse X (2008) Surgical inaccuracy of tumor resection and reconstruction within the pelvis: an experimental study. Acta Orthop 79(5):695–702
7. Imanishi J, Choong PF (2015) Three-dimensional printed calcaneal prosthesis following total calcanectomy. Int J Surg Case Rep 10:83–7
8. Sharma N, Aggarwal LM (2010) Automated medical image segmentation techniques. J Med Phys 35(1):3–14. https://doi.org/10.4103/0971-6203.58777
9. Mahajan A, Samuel S, Saran AK, Mahajan MK, Mam MK (2015) Occupational radiation exposure from C arm fluoroscopy during common orthopaedic surgical procedures and its prevention. J Clin Diagn Res 9(3):RC01-RC4. https://doi.org/10.7860/JCDR/2015/10520.5672