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REVIEW ARTICLE

3D printing from diagnostic images: a radiologist's primer with an emphasis on musculoskeletal imaging—putting the 3D printing of pathology into the hands of every physician

Tamir Friedman[1] · **Mark Michalski**[1] · **T. Rob Goodman**[1] · **J. Elliott Brown**[1]

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Abstract Three-dimensional (3D) printing has recently erupted into the medical arena due to decreased costs and increased availability of printers and software tools. Due to lack of detailed information in the medical literature on the methods for 3D printing, we have reviewed the medical and engineering literature on the various methods for 3D printing and compiled them into a practical "how to" format, thereby enabling the novice to start 3D printing with very limited funds. We describe (1) background knowledge, (2) imaging parameters, (3) software, (4) hardware, (5) post-processing, and (6) financial aspects required to cost-effectively reproduce a patient's disease ex vivo so that the patient, engineer and surgeon may hold the anatomy and associated pathology in their hands.

Keywords Additive manufacturing · Rapid prototyping · 3D printing · Stereolithography

Introduction

Three dimensional (3D) printing—also termed stereolithography, rapid prototyping and additive manufacturing—is a decades old technology that allows the low-cost manufacturing of a single item from a computer 3D file [1–3]. It has recently come to the attention of the medical field because of the rapidly falling costs required to print a model and the development of inexpensive or free 3D manipulation tools [4]. Its uses in clinical medicine and medical education are rapidly expanding and include any situation in which an exact replica of anatomy or a patient's disease would be helpful [5, 6].

Accurately translating axial images into a 3D object mentally is the art of the radiologist, but communicating complex anatomical relationships to clinicians is often challenging because verbally describing complex anatomical relationships in three dimensions is innately challenging. This problem is compounded if the clinician is not well versed in the particular anatomy and pathophysiology. Additionally, the clinician viewing the images may be falsely reassured that they understand the 3D relationship when their understanding is in fact incomplete or incorrect. A 3D computer model allows for a more intuitive understanding of the abnormalities presented for those who do not live in the "axial world" of radiologists. However, virtual 3D rendering remains limited by the two-dimensional (2D) computer monitor. The perceptive mechanisms that of our brains have evolved in order to comprehend physical objects—depth perception, proprioception and relative size—are rendered useless in this 2D world. In our experience, the advantages of holding the pathology in one's hand in order to understand the problem is of a magnitude far greater than that of 2D images when dealing with complex anatomical relationships.

Current 3D printing technology allows us to take the next step from 3D virtual renderings to creating tactile 3D models. From the axial images we can easily create an exact to-scale replica of anatomy and pathology that is specific to each patient at low cost [7]. The clinical applications of 3D printing

✉ J. Elliott Brown
Elliott.brown@yale.edu

Tamir Friedman
tamir.friedman@yale.edu

Mark Michalski
mark.michalski@yale.edu

T. Rob Goodman
rob.goodman@yale.edu

[1] School of Medicine, Department of Diagnostic Radiology and Bioimaging Sciences, Yale University, New Haven, CT, USA

are outside the scope of this document, but include patient specific preoperative planning and hardware selection/sizing, patient specific engineering, imageless surgical guidance with custom cutting jigs and drill/screw guides, patient-specific practice surgery and patient education [8].

Background knowledge

Three-dimensional printing is the lay term for "additive manufacturing" because contrary to expensive and time-consuming traditional manufacturing methods which typically require a large number of items to be produced, it can take a digital 3D file and directly create it as a physical object at the push of a button. For a single manufactured part, this is done at a comparatively low cost [9–11]. Used for decades in manufacturing, it was only first utilized in the medical field in the 1990's. It has been recently popularized because of markedly decreasing costs of printers and printer materials [12–14].

The 3D printer takes a 3D file and digitally converts it into multiple layers (just like axial cuts on a CT scan), depositing material in a 2D area that corresponds to a particular slice [10]. Layer by layer, the 3D structure forms by stacking the 2D slices which are fused together. Each printer has resolution limits, i.e. how thin it can create each layer, and varies in price from around $150 (for the "peachy printer") to $500,000 [15] for high end models. There are printers which can print almost *any* imaginable structure utilizing a seemingly endless array of materials [10] using this method. Understanding the engineering terms used in 3D printing (summarized in Table 1) is prerequisite to understanding the workflow required to go from patient imaging to a 3D print (summarized in Table 2), which we review here.

Best imaging sequences to use

Many factors contribute to the success of 3D reproduction from medical imaging. Generally, the utilization of slice thickness 1 mm or less is recommended for purposes of 3D printing [16]. If slices are thicker, the 3D reproduction may not be true-to-life or have a stepwise unevenness of the surface that may not be very recognizable after it has been printed. In this case, smoothing algorithms and interpolation between slices to produce an aesthetic print may be utilized. Smoothing algorithms, however, do not improve upon the slice resolution and small anatomic detail is lost in the approximations inherent to the algorithm.

High contrast between the object of interest and the surrounding anatomy significantly shortens the time required to segment the structure because computer automated methods are effective only in high-contrast imaging [17] and this fact should be taken into account when planning a 3D model.

Best modalities to use

CT *Best for bony anatomy.* Use the smallest field of view possible and center on the object of interest. Use a standard, rather than bone algorithm. The bone algorithm creates artifact along the bone-soft tissue interface that the computer interprets as an increase in density, decreasing the accuracy of automatic computer methods at the edges of the structure of interest.

CT angiogram or MRI angiogram *Best for printing vascular pathology and anatomy.* If a hollow vascular tree is desired, the structure can be expanded after segmentation and then hollowed to have the lumen of the print reflect the actual lumen of the vessel after segmentation [14, 18].

Dual energy CT *Best in the setting of metallic artifact.* Artifact from metal is a much greater handicap for 3D printing than virtual 3D visualization. Dual energy protocols allow significant reduction in beam hardening artifact, thereby allowing much easier segmentation and anatomically accurate 3D printing [19, 20].

MRI Each anatomic landscape (abdomen, pelvis, extremity, etc.) will require different sequences to achieve the needed contrast for segmentation. For example, we have found that non-fat suppressed images work best for many orthopedic applications. This provides better contrast between the cortical bone, which is devoid of signal, and the surrounding fat and muscle. Fat suppression does not allow adequate discrepancy between the hypointense, "suppressed" fat and the hypointense cortical bone and tendons, resulting in difficulty for automated software to differentiate the two tissues. For non-contrast studies, we use non-fat suppressed proton-density 3D volumetric sequences, with slice thickness of 1 mm. For post-contrast studies, we use a 3D volumetric (VIBE) sequence without fat suppression using 1 mm voxels [21].

Segmentation

Segmentation is the process by which the software assigns pixels across different axial slices to create a particular 3D object (Fig. 1) [8, 22]. The process of segmentation requires export of the axial DICOM images from the PACS into a program that can "segment" different structures into 3D objects *and* export that segmentation into a 3D file format.

OsiriX is a mac-only free PACS-type software that has some simple 3D segmentation tools [23]. We use Mimics

Table 1 Glossary

Segmentation	The process by which pixels through multiple axial slices are assigned to a 3D object
Mesh	The representation of a segmented 3D object by millions of different triangles/polygons, stored as a 3D file
3D printing	Rapidly manufacturing of a virtual 3D file
.stl (stereolithography)	Most common file format for 3D files—the "jpeg of 3D", accepted by all printers, contains no color information but contains polygons that make the 3D shape and its orientation in 3D space.
.wrl and .zpr	Similar to .stl but contains color information
Inverted normal	An "inside out" triangle along the surface of the 3D part, with the outside face toward the center of the part
Shell	Within a 3D file, each 3D component or part is called a "shell". For example, two bones can be put together as a single shell, so that when one is moved the other moves with it. They can also be put into separate shells, so that one moves in relation to the other

17.0, by Materialise, which we have found to have superior segmentation tools and which can efficiently combine and merge different imaging modalities. Mimics also has low-contrast tools ideal for segmenting MRI. There are also various online services that "rent" time to use their software to segment anatomy without having to purchase an entire software bundle. Examples of such services include: Bespoke modeling from 3D Systems (www.bespokeinnovations.com/) and Shapeways (www.shapeways.com). Table 3 has a short list of common software programs used for the 3D printing workflow.

Merged imaging: dual modality or dual sequence

In some cases both MRI and CT images are available for a given pathology such as images from a diagnostic MRI and from a subsequent CT performed for biopsy guidance. These may be combined to facilitate easier and more accurate segmentation. For instance, CT greatly simplifies the segmentation process of the bones and has high resolution. The CT can either be segmented separately and then merged with the MRI, or merged with the MRI prior to segmentation, to create a higher contrast image. Figures 2 and 3 illustrate this by showing a T1-weighted contrast-enhanced fat-suppressed MRI scan that was combined with a non-contrast CT scan resulting in a new data set that has the appearance of a contrast-enhanced CT scan. The final print (Fig. 4) illustrates the effectiveness of this approach.

Different MRI sequences within the same study, which inherently attain higher contrast resolution for varied structures, may also be combined in the same way. For example, utilizing the T2-weighted sequences for necrotic portions of a tumor and post-contrast sequences for the enhancing portions of the tumor, can be added to an MRI angiogram in order to segment the vessels. The osseous structures can be segmented from a CT scan and subsequently merged with the varied MRI sequences. This can be done in relatively few steps, which greatly accelerates the segmentation process.

Additionally, while different sequences/studies can be combined *prior* to segmentation to maximize contrast, the different structures from different modalities/sequences can be segmented separately into 3D files and *subsequently combined as 3D files* rather than as axial slices. This is accomplished by orienting them appropriately in 3D space, which can be performed easily using N-point registration in Mimics (Materialise). An example of this method is shown in Fig. 5.

Table 2 Overview of workflow

1. High contrast imaging via CT or MRI (slice thickness more than 1 mm)
2. Import the software into a segmentation program that has the ability to export the 3D file in .stl format (see Table 3) Export the ". stl" file
3. Edit the resulting 3D "mesh" and remove all the errors that would cause the print to fail (see Table 3 for software tools)
4. Create a base for the part to sit on or connect the different parts of your print so they keep their 3D relationship in real 3D space
5. Choose the appropriate type of material for your print. Once you have your file, there are many companies that will print it for you in almost any material
6. Print: Upload your .stl file to the printer or online 3D printing store and orient it for the most efficient way of printing. Make sure separate parts are separated on the virtual printer bed or you will be buying a dremel tool when your print is done
7. Post-processing prints: For certain printers, such as a powder printer, you need to "infiltrate" the part in a hardener, such as epoxy or cyanoacrylate (commercially available from the company "Loctite" as "Super Glue" and "Permabond" as well as 3D System's "ColorBond" (3D Systems); the print can otherwise be quite fragile

Creating the mesh and 3D file formats

After segmenting the anatomy and associated pathology, the computer takes the surface of the part, however complicated, and breaks it down into millions of simple polygons (triangles) of infinite different shapes that form the surface. This is called the "mesh" [24]. Figure 5 shows all the simple triangles used to form the complex shape of a tumor together with the scapula outlined in black (Fig. 5).

The conglomerate of polygons is then stored as a 3D file. Not all segmentation and 3D visualization programs can

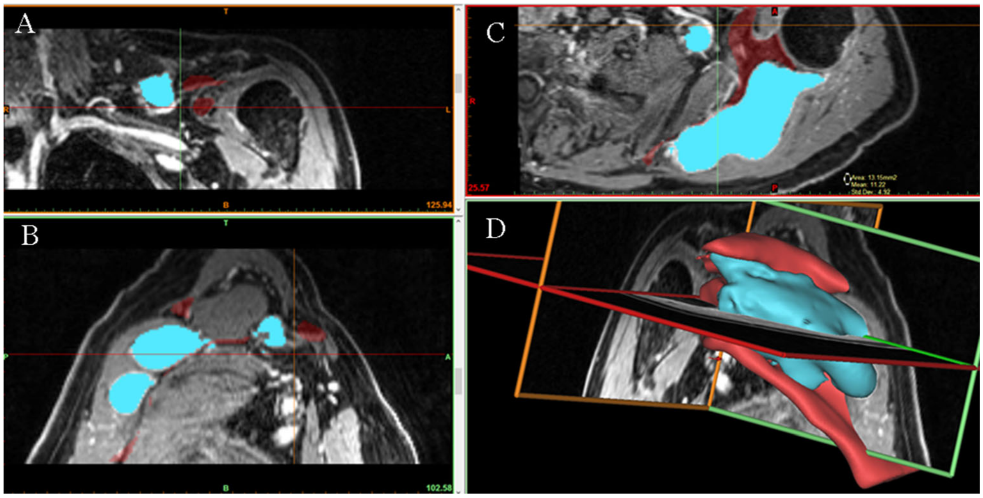

Fig. 1 In segmentation, an object of interest is assigned to a discrete 3D volume on sequential cross sections (it can be done in any plane). Here, an axial (**c**) T1 post-contrast VIBE sequence with reformatted coronal (**a**) and sagittal (**b**) planes was used to segment both a tumor and the scapula. The tumor was colored blue on each axial slice (**c**) using computer-aided methods. The computer assigns all blue pixels, which span across multiple axial slices, to a 3D volume for the tumor. This can be seen in the coronal (**a**) and sagittal (**c**) images. The resulting 3D volume is seen at the *bottom right* (**d**) with the standard imaging cross-sectional planes superimposed for reference. The scapula was colored *red* and assigned to a separate object throughout the entire figure (**a**–**d**)

export to a 3D file. There are dozens of different 3D file formats that can represent a mesh. The industry standard for a 3D file format is the ".stl" (Stereolithography or Standard Tessellation Language) file, which is analogous to the .jpeg of 2D images from your digital camera. In addition to the 3D shape, the .stl file also represents the *position* and *orientation* of the 3D object in space. This allows multiple meshes that are related to one another to retain their orientation with respect to each other. The .stl format only encodes the surface geometry of the 3D object desired and does *not* contain color or texture information. If a color print is desired, other 3D file formats are needed such as .zpr (Zcorp), .vrml (Virtual Reality Model Language) and .wrl (Virtual Reality Modeling Language – VRML). Extensive tutorials on these and other 3D formats are available online.

Expert tip: The more polygons included corresponds to a longer computational time required to manipulate, visualize and correct the errors of the mesh, but leads to a more accurate corresponding mesh. Some segmentation and mesh editing programs allow for consolidation of the polygons without losing significant detail, but significantly decreasing the processing time for visualization and editing. This can be quite helpful if the computer used has a low-end video card or central processing unit (CPU). Understanding that the 3D shape created (the mesh) is in fact composed of millions of polygons is essential for the next step in 3D printing—fixing mesh errors.

Mesh correction and common mesh errors

Once a mesh has been created, it must then be imported into a program that can evaluate the mesh for errors by ensuring it is "manifold." Virtual 3D models are mathematical representations of a shape of an object. The term "manifold" is a mathematical term used to describe the topology of a virtual object. Practically, this means that the object must have a continuous inside and a continuous outside (with no holes) and has a positive, non-zero volume. Being manifold is important because manifold correctness needs to be verified by a software program before the object is deemed printer-ready. Mesh errors can occur while the computer forms the triangles from the discrete surface points of a structure. These triangles have an inside face and an outside face. Mesh errors occur when these

Table 3 Software needed

Segmentation and export	Edit mesh errors	3D computer planning, manipulate mesh, connect structures, etc.
1. Mimics (Materialise) 2. OsiriX (Mac only , free version) 3. Vitrea workstation (not thin client) 4. 3D slicer (Harvard) 5. Paid online service (Bespoke Modeling and Shapeways)	1. 3Matic or Magics (Materialise) $ 2. Meshlab - free 3. NetFab - free	1. 3Matic, Magics or Surgicase (Materialise) 2. Blender (free) 3. 3D art programs such as Zbrush, Maya, Mudbox (autodesk)

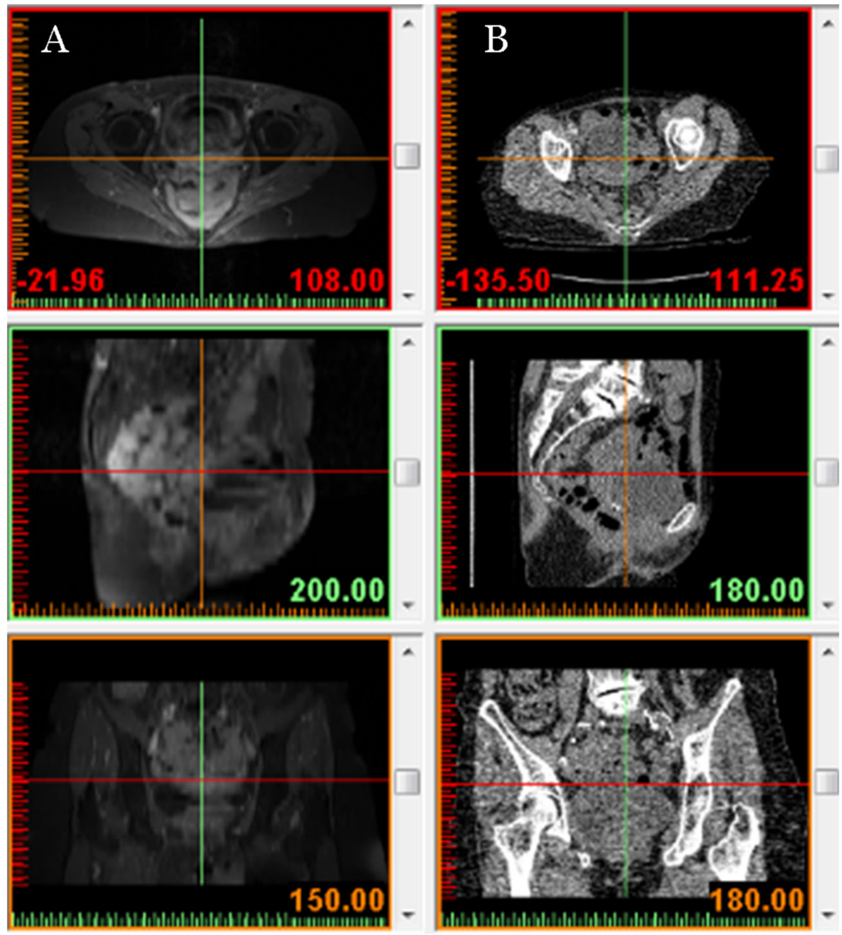

Fig. 2 Fusion of different modalities: Contrast enhanced T1-weighted fat-suppressed MRI (**a**) and non-contrast CT (**b**) studies were combined in Mimics Software (Materialise) through the dialogue box shown here. Distinct anatomic landmarks that can be found on both studies are designated by the user such as the coccyx and inferior iliac spines. The computer then uses those points to re-align the data sets and combine the images into a new stack of axial slices that contain the resolution of the non-contrast CT and the contrast resolution of the MRI as seen in Fig. 3. This gives the appearance of a contrast-enhanced CT scan

triangles are inside out, intersecting one another, or when they have a number of other orientations that may exist in the virtual arena but are not rational in physical space.

A failed print is the bane of the 3D printing process and may prove to be the most frustrating and time-consuming part of the print. If this important step of mesh correction is skipped, the printer may encounter a polygon that does not fulfill criteria for print completion, and though the part may be 90 % complete, the print will fail, resulting in wasted time and material. The failed print will require restarting from the beginning after correction of the error.

The requirements for a robustly prepared, manifold mesh include the following:

1. There may be no "inverted normal." The triangles have an orientation to each face–an outside and an inside. An inverted normal is an "inside-out" triangle whose outside face is pointing into the center of the part (Fig. 6). If all triangles of an object were inverted, the computer would see the part as having a negative volume.
2. There must be no overlapping or intersecting triangles in the mesh (Figs. 7 and 8).
3. Extraneous faces or edges may be hidden within the 3D structure. Since each polygon has an inside and outside face, having a triangle within the structure gives the part an "outside" on the "inside"—or within the internal structure of the object. These extra edges or faces are not visible from the surface/outside of the object and may be subtle (and therefore not shown). This error can come from placing two objects over the top of one another without doing a Boolean union, a concept subsequently explained.
4. It must be water tight—the mesh must have a contiguous surface of triangles with *no holes*. Even if a hollow part is required, the inner surface of the hollowed part needs to be "coated" with triangles that face *away* from the printed material [25] (Fig. 9).
5. Each polygon must share edges with adjacent triangles with no space in between. Polygons that do not share surfaces are labeled as "bad edges" (Fig. 10).
6. Shells that are touching at a single point, a single line or single plane are not manifold (Fig. 11). The connecting

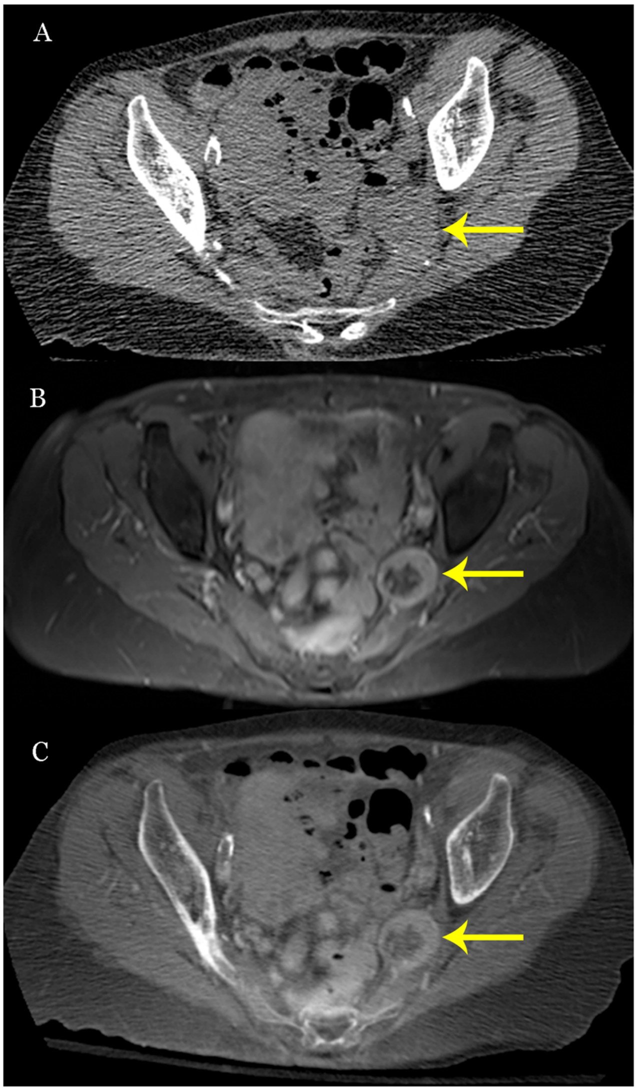

Fig. 3 Fusion of different modalities Before/After: **a** contrast-enhanced T1-weighted fat-suppressed MRI where a nerve sheath tumor (*yellow arrows*) spanning the left sciatic nerve is well seen; **b** non-contrast CT scan where the bone is well seen, but the tumor is poorly differentiated from the surrounding soft tissue; **c** fused MRI and CT images performed in Mimics (as per Fig. 2) showing *both* the bony and soft tissue anatomy in exquisite detail, appearing as a contrast-enhanced CT scan

point/edge/plane would be mathematically infinitely thin and therefore have no volume, meaning there was nothing to print. The intersection therefore could not be made. Solve this issue by creating a very small but non-zero connection between the objects.

7. There should be no "noise shells". Noise shells are unwanted/unintended islands of 3D shells separate from the main shell/mesh, which may have been mistakenly segmented by the computer as on object. This can occur for a variety of reasons such as a focus of calcium in a vessel being mistaken for a "bone" by computer algorithms. Eliminating "noise shells" decreases the number of errors you have to find and correct (Fig. 12).

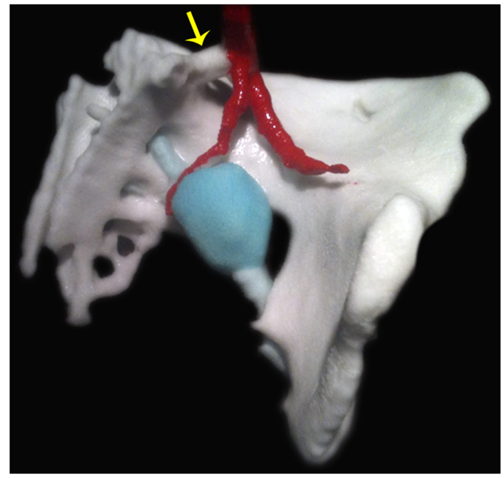

Fig. 4 3D print nerve sheath tumor: This is the final 3D print of the nerve sheath tumor involving the left sciatic nerve in Figs. 2 and 3. The *yellow arrow* is a non-anatomic cylinder used to connect the blood vessel to the bone so that the appropriate anatomic relationship was maintained after printing. Other cylinders used are situated behind the vessel and not visible in this projection. This demonstrates the artery (*red*) draping over the lesion (*blue*), which was found to be intimately associated with the lesion at the time of surgery and sacrificed as part of the resection. This was printed on the z450 powder printer (3D Systems) because it allowed us to color the different structures to contrast them against the white bone. Powder printers are among the few printers that can print in full color. The print was requested because it was difficult to ascertain from the axial data set if the lesion would need a purely anterior approach or if a second approach through the gluteal muscles was needed

Mesh editing software

Most 3D printers have their own simple proprietary mesh editors. Meshlab is a free open-source software for both Mac and PC and can help mesh edits [26]. Netfabb is another free mesh-editing software. Also

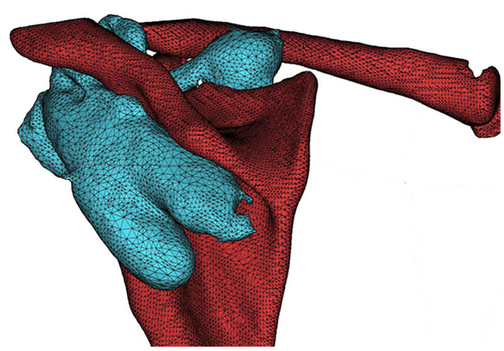

Fig. 5 The mesh: *Outlined in black* are the edges of many simple triangles that the computer uses to represent the more complex shape of this scapula (*red*) and tumor (*blue*). Collectively the triangles are referred to as a "mesh". Not all triangles that can exist in virtual space can exist in physical space. Care must be taken that each triangle is "following the rules" (see section entitled "Mesh correction and common mesh errors" for details). *Blue* indicates tumor, segmented from an MRI as in Fig. 1, and the *red* indicates bony scapula, segmented from a CT scan. The two meshes were "merged" after segmentation using N-point registration in the Mimics software

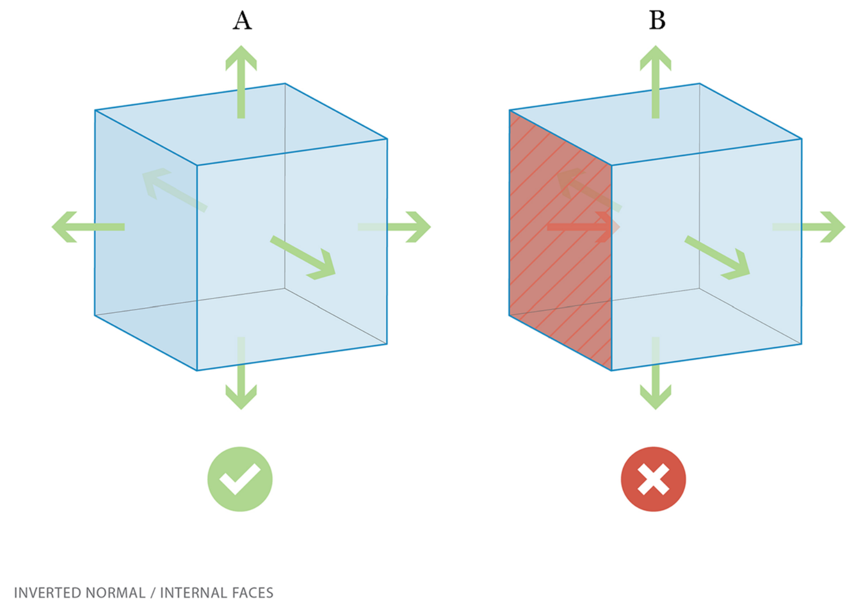

Fig. 6 Inverted normal: Each triangle used to represent an object has a face orientation—the outside face of each triangle (*blue*) must be facing the outside of the part as in the first part of the figure (**a**). If the inside face (*red*) is facing outward, as in the second part of the figure (**b**), an "inverted normal" error results. Inverted normals can cause a shell to have a "negative" volume (an inside out shape). This can be problematic if Boolean operations such as subtractions or additions are performed or if the volume of an object is required for research purposes. It will also cause a print to fail

Blender is a free open-source software for both Mac and PC that can be used to edit meshes [27]. We use 3Matic from Materialise, but Magics from Materialise is also a proven mesh editor.

Many software products fix errors automatically. The 3Matic software from Materialise has a "wrap" function that creates a new shell around the part, fixing most errors quickly when the automatic function fails. Another simple method to remove errors arising from mesh creation that the software is unable to perform automatically is to select the polygons surrounding the error and delete them all (which creates a hole in the mesh). Once a hole has been created in the mesh, it can be filled with new surface polygons. Mesh correction proves to be a relatively simple endeavor when the terminology is understood. Thoroughly rechecking the mesh for errors after editing will save time and resources.

Manipulating the mesh

Mesh manipulation may prove compulsory for planning virtual surgery or connecting different parts of the anatomy together.

Connecting the parts

Segmented parts can keep their proper relationships in virtual 3D space without a problem; however, when parts are printed, they are subject to gravity and if not properly connected, will fall apart. For example, if there are arteries or veins running next to a tumor, a cylinder or other geometric shape will need to be created in order to bridge the gap between the pieces and maintain the anatomic relationship between the related structures. The cylinders must be positioned to connect the pieces

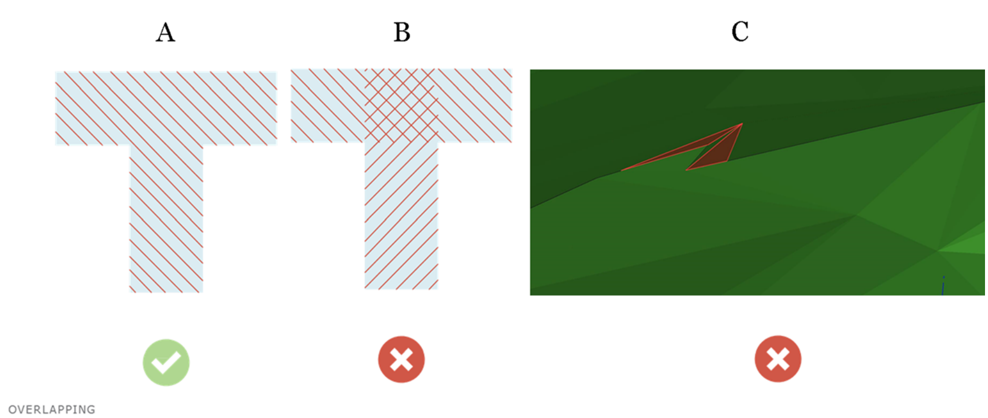

Fig. 7 Overlapping triangles: The object must not contain any overlapping structures or triangles. **a** The two rectangles were merged so that they contained one continuous surface. (**b**) Here they were not merged, resulting in overlapping triangles which will cause the print to fail. **c** This is a zoomed-in image of the surface of a part to be 3D printed, showing a real-life example of two overlapping triangles (*orange*). Overlapping triangles cause an outside face of a triangle to be within the volume of the part, rendering the mesh "non-manifold"

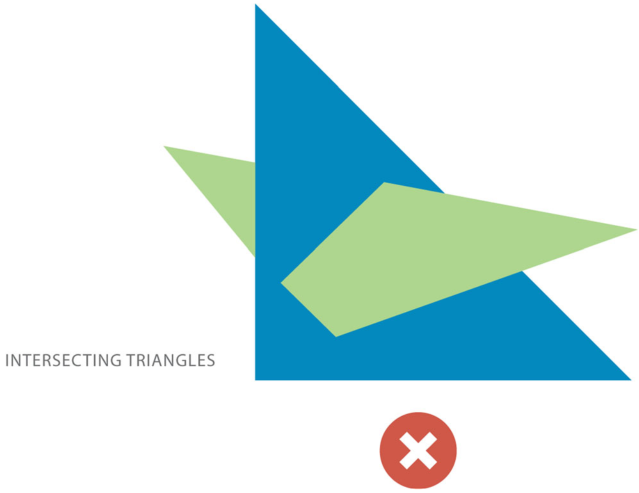

Fig. 8 Intersecting triangles: This image illustrates intersecting triangles. In physical space, the outer surface of an object cannot intersect with itself. Only one triangle may exist in a given coordinate. This error is caused when the computer connects discrete surface points of the segmented volume into triangles but in an orientation whereby the legs of the triangles intersect one another

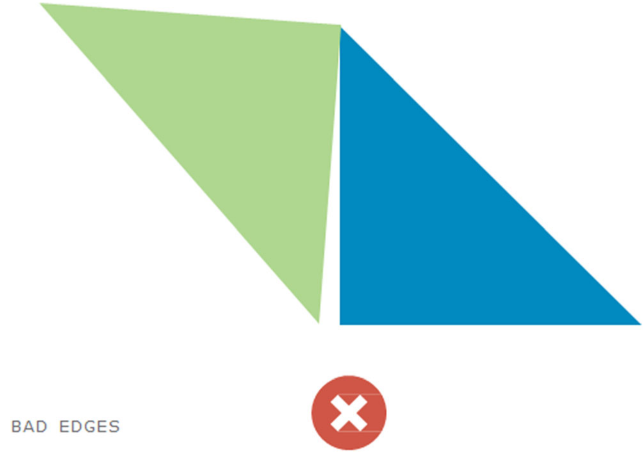

Fig. 10 Bad edges: This is an example of a "bad edge" as the computer rendered the two triangles close, but not sharing every point along one of the edges. All triangles must be contiguous, without gaps

and a Boolean addition is necessary in order to "add" the cylinder to the pieces (Fig. 4).

If a part must be connectable but also removable, such as fracture fragments, bones or a tumor within an organ, this can easily be achieved. A new object may be created in the mesh-editing program, such as a cylinder, and placed in a position that spans the two pieces. Once the first cylinder is created, it is then copied and made 0.25–0.5 mm larger in diameter. Then a Boolean subtraction is performed using the larger diameter cylinder in one of the parts, creating a "negative" of the cylinder in the printed part (i.e. a hole that is .25 mm larger than the "male" cylinder). The smaller cylinder can be added to the opposite part as the male connector. If a free connector is desired, the Boolean subtraction can be performed on both pieces to be joined, and the connector printed separately or a wooden fluted dowel that fits the hole can be purchased at a hardware store, resulting in the ability to insert the male cylinder/peg into the hole that now has a 0.25–0.5-mm tolerance. Multiple pegs may be made; however, care must be taken to ensure they are in exactly the same spatial orientation/angle, otherwise only one of the pegs can be used to fit the parts together (Figs. 13 and 14).

3D computerized surgical planning

3D space allows for planning screw trajectory, size and placement. A "negative" of the surface of a part (for example, a bone such as a mandible) can be printed, thus providing the surgeon with a printed negative that matches the anatomy from the surgeon's dissection exactly. This printed negative may be fitted with drill and/or cutting guides at specific, predetermined angles. The printed negative fits perfectly onto the bone and the holes drilled and angles cut are exactly as predetermined, which

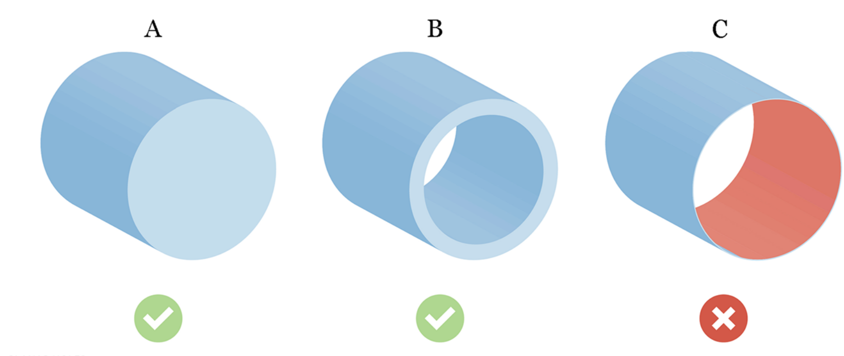

Fig. 9 Planar holes: The surfaces of the objects must be represented by continuous triangles—no holes (absent triangles) may exist from the surface and it must contain an inner and outer surface. **a** The object is solid without any holes with the outward face colored blue. **b** While there is a "hole" in the cylinder, there is a continuous surface of outward-facing triangles (*blue*) on the outer perimeter as well as the outside surface of the hole. The inward-facing triangles cannot be seen. **c** There is a hole in the mesh, revealing the inner-facing triangles (*red*) of the outer surface (*blue*). This object is represented only by infinitely thin triangles and therefore has an infinitely small, non-zero volume. This print will fail

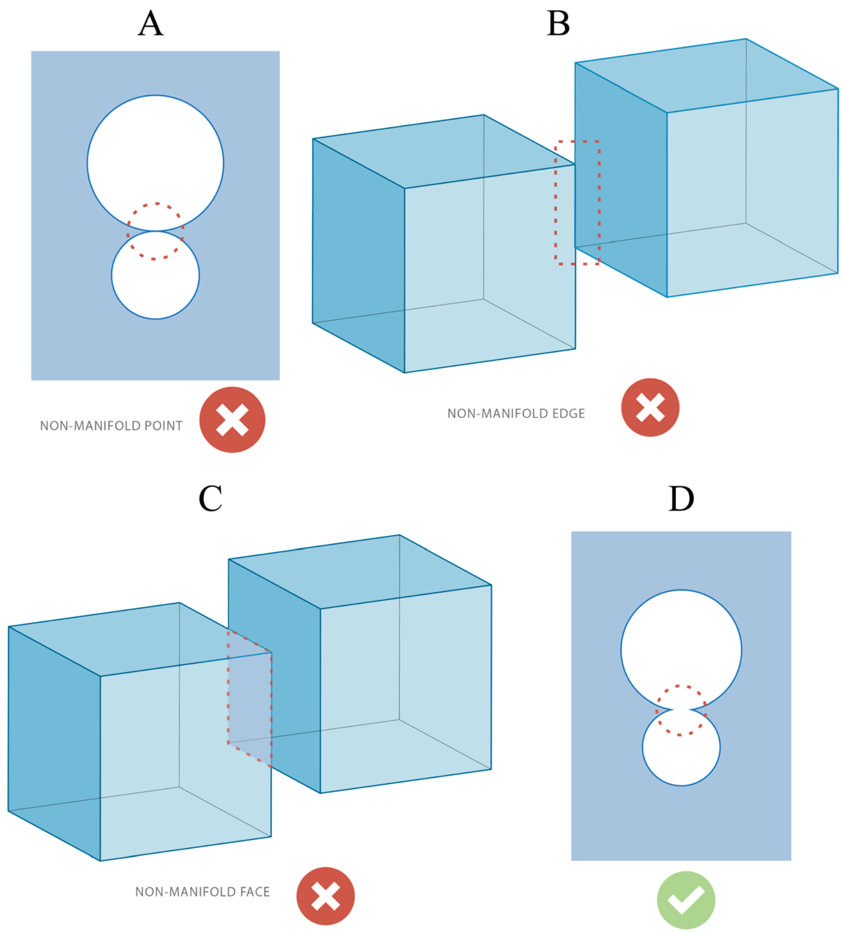

Fig. 11 Non-manifold error: More examples of a "non-manifold" error—there must be more than a single point (**a**), single line (**b**) or single plane (**c**) of contact between the objects that are considered a single shell. These connections have a non-zero infinitely small volume and are therefore not printable. Solve this problem by creating a larger connection between the objects (**d**)

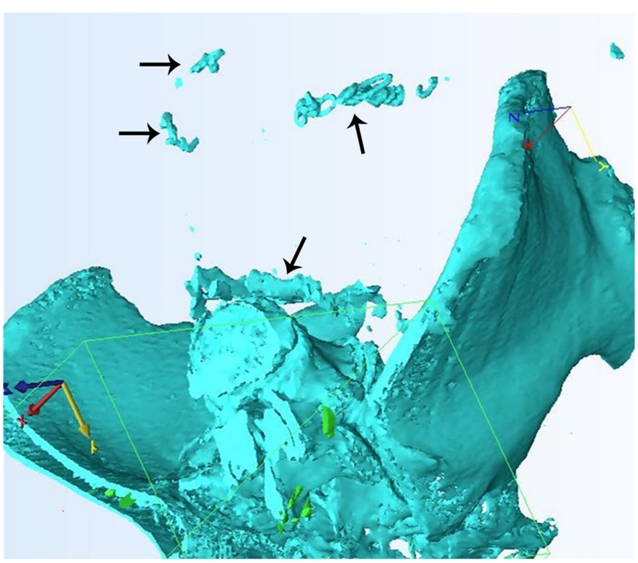

Fig. 12 Noise shells: Note the islands of calcium which were segmented as "bone" when the computer segmented this pelvis and sacrum (*black arrows*). These are unwanted small shells called "noise shells." These shells often contain many mesh errors, which can all be eliminated by deleting these shells

eliminates human error and the time-consuming nature of freehand estimates [28, 29]. This was first shown in mandibular reconstructions, where a vascularized fibula flap must be shaped to match a mandible; also it can be done virtually with angles from the patient's mandible measured and the fibula "cut" at exact angles to match the native mandible. A negative of the fibula is printed with these angles printed as linear holes in the part, creating a cutting guide, allowing the surgeon the ability to, within minutes, overlay the print on the fibula, put their blade through the holes, and cut the exact angles. The surgeon can also pre-bend his/her plates on the planned reconstructed mandible that is printed in advance [30], which has also been used to eliminate expensive CT guidance systems for complex spinal hardware placement [28, 30].

An organ may be virtually "dissected" so that the surgeon can dissemble the print and see the tumor in the substance of an organ, or virtually "reduce" a fracture to enable the surgeon to pre-bend his/her internal fixation plates. In the absence of a printed part, the same software allows the surgeon to premeasure angles to aid in presurgical planning such as described in the case of a malunited radius (Fig. 15). Angles of deformity were measured on the 3D object, and planes were used to cut at angles calculated to correct the deformity. The radius was

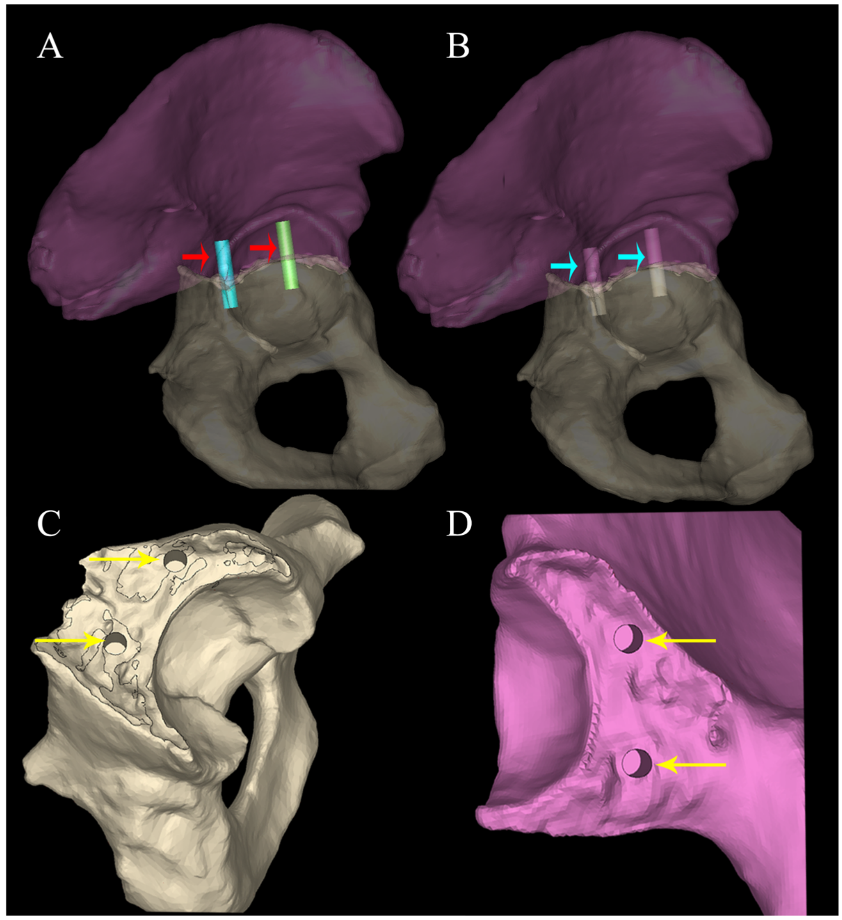

Fig. 13 Virtual connecting of the parts: A computer rendition of a transverse acetabular fracture with upper and lower fragments. **a** The colored pegs (*red arrows*) were sized 0.5 mm larger than fluted dowels from the hardware store, and placed in a parallel orientation across both superior and inferior parts of the fracture. They were then subtracted out of both "shells" of the fracture using a Boolean operation (notice holes in part **b**, *blue arrows*). **c**–**d** This resulted in hollow cylinders that could be printed in the final part (*yellow arrows*), which allows the parts be connected with fluted dowels available at the local hardware store, for a "press fit", allowing the user to separate and connect the object multiple times, much like a puzzle piece, and inspect each piece individually as well as a whole

then re-aligned and the results of the correction inspected. The corrected radius can then be printed and the plates pre-bent on the "corrected" print.

Aligning parts

Parts may need to be aligned before printing for several reasons, i.e. fracture reduction or superimposition of a soft tissue tumor on/within a bone. This can be done as long as they have been made as separate .stl files, and is easily performed in Materialise 3Matic software to create a point-point registration (N-point registration) to properly orient the pelvic fracture from a CT. Opposing points from each fracture component are chosen and the computer reorients the parts so that those points are touching (Fig. 16).

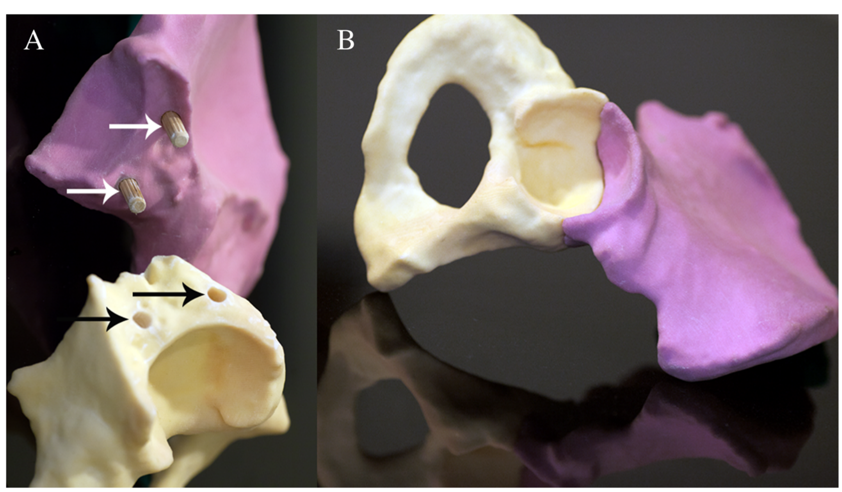

Fig. 14 3D-printed transverse acetabular fracture. **a** Demonstrates the holes which were created virtually and into the part (*black arrow*). Fluted dowels from the local hardware store press-fit tightly into the holes (*white arrow*) and allow the two pieces to remain together without being held (as seen in **b**), but also come apart

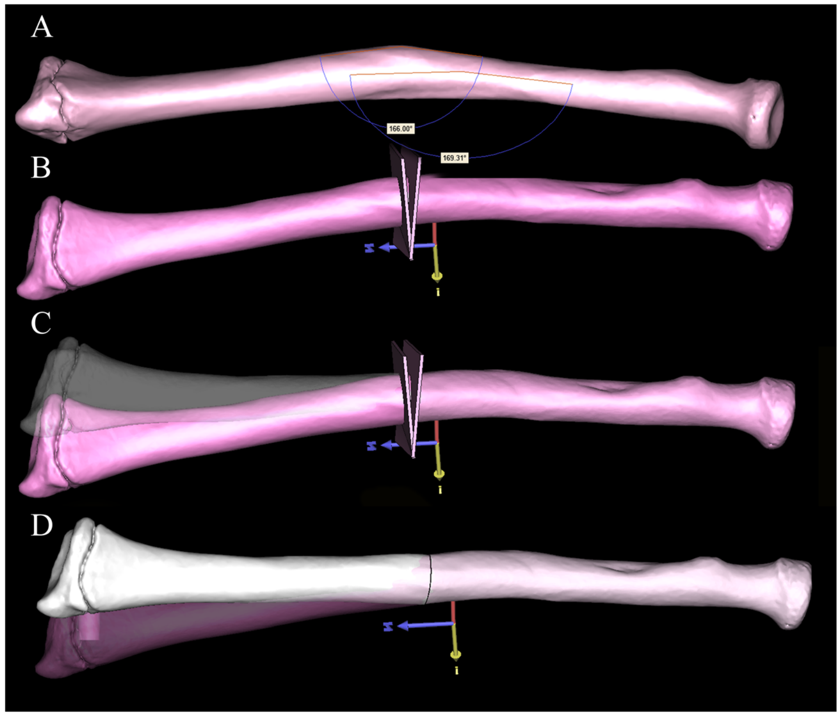

Fig. 15 Virtual surgery. Demonstrates a virtual correction of malunion of a radius. **a** Note the angles measured along the 3D surface of the deformity. Virtual cutting objects are made at the appropriate angles (**b**) and then the radius malunion is virtually corrected (**c**) and the final proposed plan is shown (**d**). This aided the surgeon in deciding how to perform the osteotomy. Cutting jigs can be made for the surgeon to use intraoperatively, obviating the osteotomies freehand

Removing the intersecting volume for puzzle-piece-like fitting

In order to print separate pieces that fit together precisely like a puzzle, the two parts must be perfect negatives of each other (such as a fracture). There are very small errors that may be introduced during the segmentation and mesh creation process making intersecting (occupy the same virtual space) components of the two puzzle pieces. These errors/intersections need to be removed to allow for puzzle-like part fitting. To accomplish this, the two meshes will have to be aligned (as in the preceding). Once aligned the software can identify the volume of intersecting components of the two meshes and create a new “shell” representing that volume. A Boolean subtraction is then performed by subtracting the intersecting volume from at least one of the fracture components and then checking again for mesh errors. This ensures the opposing surfaces are perfect negatives of each other, so they can fit together like a puzzle piece (Fig. 17).

Printing methods or manufacturing process and materials explained

The item is now ready to be printed. Decisions regarding (1) type of printer (2) type of printing material and (3) printing methods must now be made. There are many different methods, depending on the desired material, speed, accuracy and cost, which include but are not limited to:

1. Fused deposition modeling (FDM)
2. Multijet printing (MJP)
3. Gypsum powder printers
4. Stereolithography (SLA) and its close cousin digital light processing (DLP)
5. Selective laser sintering (SLS) (used in creating metals and plastics that are implantable in the human body)

Fused deposition modeling

The most common printing method is fused deposition modeling (FDM) where thermoplastic materials are melted and extruded through a nozzle (extrusion head) that adds material layer by layer, much like a computerized glue gun [31].

Advantages Models can have high tensile strength and remain waterproof, similar to that of the children’s toy “Legos”. Models are also impact resistant and are currently more cost-effective than the resin-based systems.

Disadvantages Malodorous fumes as the material is melted need to vented. Since material is continuously deposited, much like a continuous hot glue gun, the extrusion head must continuously move, otherwise there are focal areas of material build-up. Additionally, the material sags during printing when unsupported pieces are perpendicular to the build axis, such as in overhangs. Therefore, supporting structures may need to be constructed and later removed. The material is also sensitive

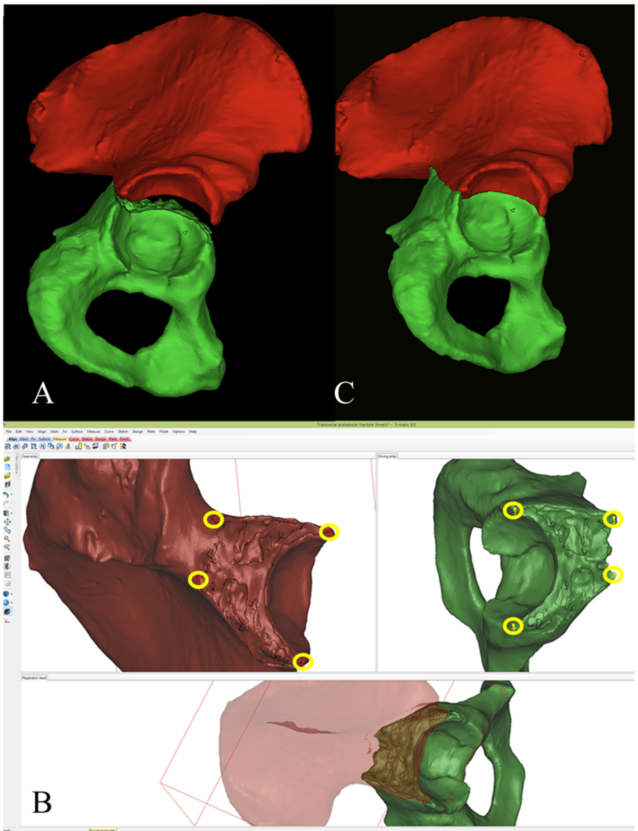

Fig. 16 Part alignment: **a** The minimally displaced fracture is noted. Because it was desired that the parts fit together perfectly, reduction of the fracture was performed virtually using “N-point” registration in Mimics Software. Anatomically distinct points, which matched on opposing parts of the fracture, were selected. The computer re-oriented the inferior fragment (*green*) to match the upper component (*colored red* in **a** and **c**, colored *brown* in the registration dialogue box (**b**). Once the pieces are closely aligned, “Global registration” can then be used, which uses thousands of points along the fracture margins to better align the two fragments

to labile temperatures that may cause drooping of the desired part. The manufacturing time of the given part also tends to be longer than similar constructed parts on particle-based printers (see the following). The surface of the part is often lacking in detail and can leave a “stepwise” or “ribbed” exterior. One hundred micron layers are achievable even in cheap consumer-based systems; however, the time to print a usable part is dependent on the material used because each layer must cool partially before the next layer can be placed.

Common supplier companies: Makerbot, Hewlett Packard, 3D systems

The most common materials used in FDM are thermoplastics that include:

1. *Acrylonitrile butadiene styrene (ABS)*. Crude-oil based, cheap, slightly more flexible than polylactic acid but sensitive to ultraviolet light causing it to riddle. It also releases toxic fumes while printing and needs adequate ventilation [32, 33].
2. *Polylactic acid (PLA)*. Environmentally friendly, made of natural materials and biodegradable (the colors may contain toxins). Releases no toxic fumes [34].
3. *Polyvinyl alcohol (PVA)*. This is used as a support material for printing very delicate parts that extend beyond their base and would otherwise droop without support while the plastic is hot [35].
4. *Nylon*. Cheaper than ABS and PLA, but releases toxic fumes [8].
5. *Ethylene and Polycarbonate plastics*. Durable, can be printed crystal clear, chemical resistant.[35]. Cons: very high extrusion temperatures.

Multijet and polyjet printing

These utilize inkjet technology to deposit photopolymers (some are thermoplastic as well), which are cured/hardened with ultraviolet light. It can have multiple heads to deposit multiple different materials, and uses support material around the part.

Advantages Multiple materials available in multiple colors and textures. Layer thickness is as low as 16 μ, allowing for the creation of very fine high-resolution structures. Additionally the support material may be easily removed after the part has been printed using a melting process (if support is wax) or a chemical reaction (if support material is not wax such as Propylene, Polyethylene, Acrylic monomer, or Glycerin).

Disadvantages Expensive to own and operate. Parts can be brittle; however, innovative rubber-like materials have recently rectified this traditional drawback.

Materials Uses many different composite materials that may be colored, tinted, or clear with a wax-based support material that is subsequently melted away. Proprietary names include VisiJet Crystal and VisiJet Procast.

Companies 3D systems, Stratasys, Agile manufacturing, among many others.

Light/resin based printers

Digital light processing (DLP) and stereolithography (SLA) are resin-based printers. These printers use a vat of liquid resin that is sensitive to light. A laser or a DLP projector (the same projector that are used to give presentations) “cures” the layer of resin. The level of the resin rises and the laser cures the subsequent layer. The

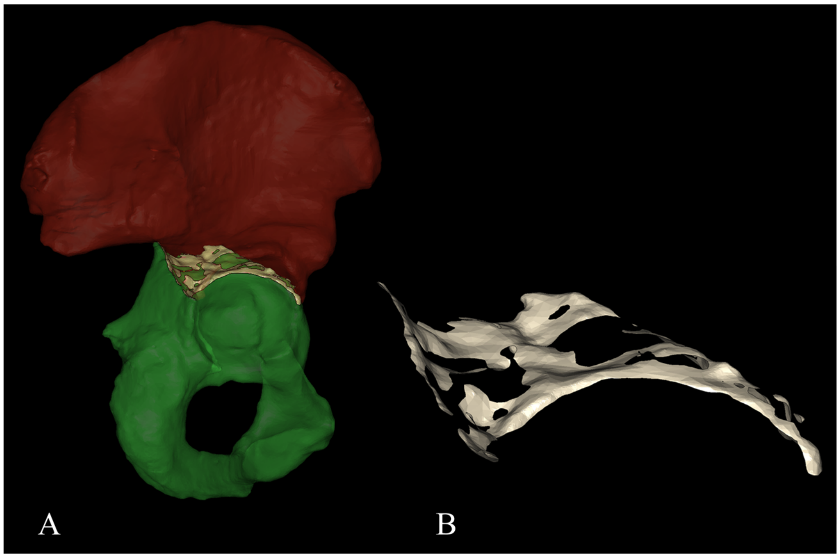

Fig. 17 Removal of overlapping pieces when reducing a fracture. **a** The superior (*red*) and inferior (*green*) pieces of the transverse acetabular fracture above were segmented separately. Due to small errors in the segmenting, mesh-forming and mesh correction and virtual fracture reduction process (if reduction is not perfect, there will be gap or overlap), very small overlaps of the two fragments, called "the intersecting component" (*white*), were found. These may seem insignificant, but preclude perfect fitting of the two fragments. The "intersecting" volume (**b**) was created as a new shell, and then subtracted from one of the other shells. This ensured a puzzle-like fit of the fracture when printed in physical space

materials can be of various colors, semi-transparent or transparent.

Advantages Fast, accurate, smooth surface finish, down to 50-μm layer thickness.

Disadvantages Support structures must be added for overhanging parts, which must be manually cut off after the print. Post-printing curing in an oven is sometimes required to fully harden the resin. Some resins lose stability over time and become brittle.

Powder-based printers

Finely milled material, including gypsum (for biomodels) or human-implantable materials metals (such as titanium) or high performance thermoplastics such as OXPEKK®-MG (Oxford Performance Materials) is spread onto the build tray. A laser "cures" the metal or thermoplastic layer by layer. In the case of gypsum, glue is spread onto each successive layer, like an inkjet printer [36].

Advantages Gypsum printers: fast, accurate, have a cheap material cost and are reliable. They are currently the only technology that can print in full color and in 100-μ layer thickness. If post-processed with epoxy, models will have a bone-like feel that can be drilled and cut like bone if practice surgery is desired. After such post-processing, it resembles porcelain, with a high tensile strength but with a low-impact resistance and will break if dropped. For metal and thermoplastic materials, this is often called "laser sintering". Its advantages are that high performance implantable materials can be used.

Disadvantages For gypsum printers, the print must be post-processed to "harden" by infiltrating it with epoxy, anabolic resin, or a water thin grade of cyanoacrylate (trade names include Super Glue and Permabond). These can be purchased

Table 4 Retail costs of a life-size model of the adult hemipelvis seen in Fig. 4

In house z450 printer: 85$
Imaterialise:
Polyamide plastic (PLA): $645
Ceramic: $95
Paintable Resin: $258
Rubber-like material: $528
Acrylonitrile butadiene styrene (ABS): $334
Transparent Resin: $318
Shapeways:
White plastic: $220.12
Metallic Finish: $383.73
Transparent Acrylic: $1103
Stainless Steel: $1,847.38
3D systems:
Most plastics: ~ $600–700
Color jet z print (similar printer to the z450 used in house): $406

at local distributers in large volumes for the manufactures Loctite or Henkel. For other implantable materials, the regulatory process must be overcome before its use. There are several commercially available products created this way such as implantable cranial implants.

Current financial considerations

There are no CPT codes specifically available for 3D printed parts; however, insurance companies pay for 3D prints if they are part of a customized surgical implant. Radiology departments can bill the surgical departments, who in turn can bill the insurance company using a presurgical planning code. Alternatively, the insurance company could be billed directly using an "unlisted" code, with material cost added to the charge. As more data is collected to evaluate the potential added value of 3D printing, in the form of decreased operating room time or complication rates, a CPT code may be created in the future. Also, check with your hospital—they may fund your 3D printing endeavors if they can use them as marketing tools to bring in more patients.

The costs of prints vary widely depending on the printer and the material used but generally is rapidly falling. The printer used for the prints described here were performed on a 3D Systems Z450 powder printer, which can cost $50,000 new, and anywhere from $10,000–$35,000 used. An annual service contract of approximately $5,000 is also necessary to keep the printer in working condition. The 3D print of the tumor around the scapula (Fig. 1) had a material cost of only $34 when printed with the z450 printer in plaster; note that does not include the cost of the maintenance of the printer. The material costs of the hemipelvis (Fig. 4) was $85 on the z450. This cost can be cut significantly if a life-size model is not needed; when this same model was printed at a 75 % scale, material cost was only $49. For comparison sake, we took the 3D file of the hemipelvis (Fig. 4), including half of the sacrum as shown, and presented it to three online retailers with various materials to evaluate the range of costs it would take to produce the same model (see Table 4).

Conclusion

3D printing is simple to perform with only a small amount of background knowledge, as described here. It allows a perfect reproduction of the patient's anatomy and disease ex vivo so that the patient, engineer and surgeon can hold an exact model of the body part in their hands and utilize for a myriad of purposes, including advanced anatomic comprehension, presurgical planning and patient education. The barriers to entering the market are becoming less each year as the tools and printers become cheaper; a complete 3D printing set up can be created for under a few thousand dollars; additionally, 3D printing can be reimbursed with a presurgical planning or unlisted CPT code. Radiology departments are well suited to provide the service, as they have access to all the data and understand the disease from the axial data set, enabling them to accurately produce a 3D model. The response we have received from our patients and surgeons to date has been overwhelmingly positive, especially for complex cases. While its utility is still being evaluated, we believe the process adds significant benefit in a variety of settings, in particular for complex cases.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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