



Digital and 3D Printed Models for Surgical Planning

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Introduction

3D visualization and printing techniques have been met with great enthusiasm by the surgical community; they potentially provide significant benefits in a wide range of clinical applications, particularly in preoperative planning [1, 2]. Preoperative planning is considered a crucial aspect of safe and effective surgery. We can broadly define preoperative planning as any activity aimed at understanding a patient's anatomy or pathology in order to inform clinical decision-making and determine an appropriate operative strategy [3]. This can involve attempts to understand specific structural relationships, preoperative rehearsal, simulation, judgments of feasibility for a given procedure (e.g., tumor resectability), physiological modeling, or implant placement/design [4, 5]. It can encompass a diverse range of activities that occur at the level of the individual surgeon or as part of a more formalized process such as multidisciplinary team (MDT) meetings.

Medical imaging plays a major role in surgical planning. Currently, clinical decisions are made after 2D imaging modalities such as plain radiographs, computed tomography (CT), or magnetic resonance imaging (MRI) are reviewed by the

surgeon and/or radiologist. However, extracting the relevant 3D anatomical relationships from 2D images in order to apply them intraoperatively can be difficult even for experienced practitioners. Intuitively, 3D reconstructions appear to have an advantage over traditional 2D images. Consequently, the interest of 3D visualization techniques in surgical specialties has increased in recent years [6].

Anatomically accurate 3D virtual models can be reconstructed from standard 2D Digital Imaging and Communications in Medicine (DICOM) data sets through a variety of methods [2]. Such virtual models can subsequently be printed as physical objects through a process termed *additive manufacturing* – more commonly known as 3D printing. Although there are various methods of 3D printing available, each relies on the principle of sequentially laying 2D layers of material in order to construct a 3D structure.

Advances in technology have facilitated dissemination of 3D modeling. Easier access to cheaper computer processing power in conjunction with the proliferation of open-source imaging and computer graphics software has made it possible to generate anatomical models on a personal computer [7]. Similarly, development of low-cost 3D desktop printers has enabled use outside industrial manufacturing. After initial pioneering work performed by oral maxillofacial and congenital cardiac surgeons [8, 9], the majority of surgical specialties have now utilized 3D

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visualization to plan and perform a diverse range of procedures [10].

Early research suggests 3D visualization may result in improved anatomical understanding [11, 12]. This may be particularly evident in cases involving highly variable, complex structural relationships [13, 14]. Proponents hope 3D models may facilitate more tailored procedures, reduce errors and complications, and ultimately improve patient outcomes [1]. Beyond pure anatomical visualization, 3D modeling could facilitate new methods of interacting with imaging data for preoperative preparation. 3D models can enable patient-specific virtual simulations and computer-aided design (CAD) of custom implants and serve as the substrate for augmented reality (AR)-enhanced navigation [15–17].

Despite initial optimism, the extent to which 3D models influence preoperative decision-making and their relative effectiveness has yet to be established. Furthermore, the ideal user (novice versus expert), specific indications, optimal user interface, and even evaluation methodology remain unknown. In this chapter, we will provide an overview of 3D reconstruction methods along with current 3D printing technology. We will outline how these techniques have been used for preoperative planning across surgical specialties to date and highlight research priorities going forward.

Methods of Generating 3D Virtual Reconstructions

Segmentation

Image segmentation is a fundamental step in 3D surface-rendered model production. *Segmentation* refers to the process by which unique labels are applied to imaging data in order to identify anatomical or pathological structures of interest [18]. This can be manual or automated to varying degrees – at present the majority of approaches require some user input.

Manual segmentation is the simplest method. The user (typically radiologist) will

manually highlight or outline relevant structures slice by slice. This can be performed with a simple mouse-controlled cursor; however, specialized devices like tablet/digital pens are preferable.

One of the principle advantages is flexibility. Manual segmentation is always applicable, even if structures are difficult to delineate owing to artifact or poor-quality imaging. However, manual segmentation can be extremely time-consuming and lacks precision or reproducibility owing to individual interpretation of scan data. Despite these drawbacks, manual segmentation is widely employed due to its ease of implementation and availability of multiple open-source software solutions.

Several different algorithmic approaches have been implemented for segmentation. A detailed discussion of this complex area is beyond the scope of this chapter. However, we provide an overview of key techniques:

Thresholding

A straightforward and fast method is termed *thresholding*. The user sets a global or upper and lower threshold for Hounsfield intensity generating a binary segmentation. Pixels are classified as either belonging to the target structure or else marked as background. This method can be extremely effective for high-intensity structures such as bone [19].

Edge-Based Segmentation

Edge-based segmentation relies on discontinuities in the image data, usually signified by rapid changes in pixel signal intensity between two different structures [19].

Region-Based Segmentation

Region-based segmentation is based on the concept of homogeneity. A target structure is assumed to possess similar pixels clustered together. With the *seed point method*, the user identifies seed points within a target structure, and a region of homogenous pixels of similar intensities is then grown iteratively. Region-growing approaches are typically used for contrast-enhanced vascular structures [18].

Atlas-Based Segmentation

In *atlas-based segmentation*, the geometry and features of organs, blood vessels, and soft tissues are compiled as an atlas. Large databases of images can be constructed, providing a rich compendium of anatomical variation within a population. Statistical shape models (SSMs) form the basis of atlas-based segmentation. SSMs iteratively deform to fit the target of new structures with shapes that are derived from the atlas training set of labeled data. Although conceptually simple, the implementation can be computationally demanding and time-consuming [18, 20].

Automatic Segmentation

Fully *automated segmentation* remains a highly desirable goal, because of the time constraints imposed by modern medicine. With “one click,” the whole task would be implemented accurately and reliably from start to finish. Despite the number of algorithmic segmentation methods (as outlined above), there remains no universal algorithm for every form of medical imaging. It is likely such an approach is unrealistic owing to the wide variation in imaging modalities, anatomical relationships, pathological processes, and biological diversity we encounter in medical imaging. Requirements of brain imaging, for example, would differ significantly from abdominal imaging.

Furthermore, automated solutions must factor in problems common to all imaging modalities, such as partial volume effect (loss of activity in small structures due to limited resolution of imaging system), imaging artifact (e.g., motion, ring, intensity inhomogeneity), and signal noise.

Key requirements of automatic segmentation include:

1. *Accuracy*: Relevant structures should be correctly identified and delineated precisely if results are to be used in clinical decision-making
2. *Speed*: Results should be sufficiently quick to enable integration into current clinical workflows
3. *Reproducibility*: Results should be similar for different users analyzing the same data
4. *Robustness*: Methods should be applicable in a wide range of scenarios [21].

Recent research has demonstrated that *convolutional neural networks* (a subset of machine learning) may help solve the automatic segmentation problem. Briefly, convolutional neural networks (CNNs) take inspiration from the animal visual cortex processing data in a grid pattern to adaptively learn spatial patterns in a hierarchical fashion from low- to high-level features [22]. Investigators from around the world have successfully applied the technique to multiple segmentation problems including brain and abdominal segmentation [23, 24]. CNNs represent a form of *supervised learning* – meaning they require large training data sets of labeled scan data.

Rendering Methods for 3D Virtual Models

We can broadly divide 3D virtual visualization into two main categories:

1. *Surface-rendered models*
2. *Volumetrically rendered models*

Surface Rendering Techniques

Surface-rendered models are based on indirect polygonal mesh representations derived from the results of segmentation. For this reason, it is alternatively known as indirect volume visualization, as the surface mesh representation is not the original data set itself.

Through segmentation, we classify each pixel of imaging data as belonging to a certain piece of anatomy. Results of this labeling are stacked sequentially, slice by slice, and used by segmentation software to reconstruct the 3D surface geometry. This can subsequently be exported as a polygonal surface mesh for further editing and processing (Fig. 8.1).

The basic unit of a mesh is a vertex, which describes a position in three-dimensional space. Two vertices joined by a straight line form an edge. A polygon is defined by three (triangle) or four (quad) vertices joined by the corresponding

From segmentation to 3D patient specific model

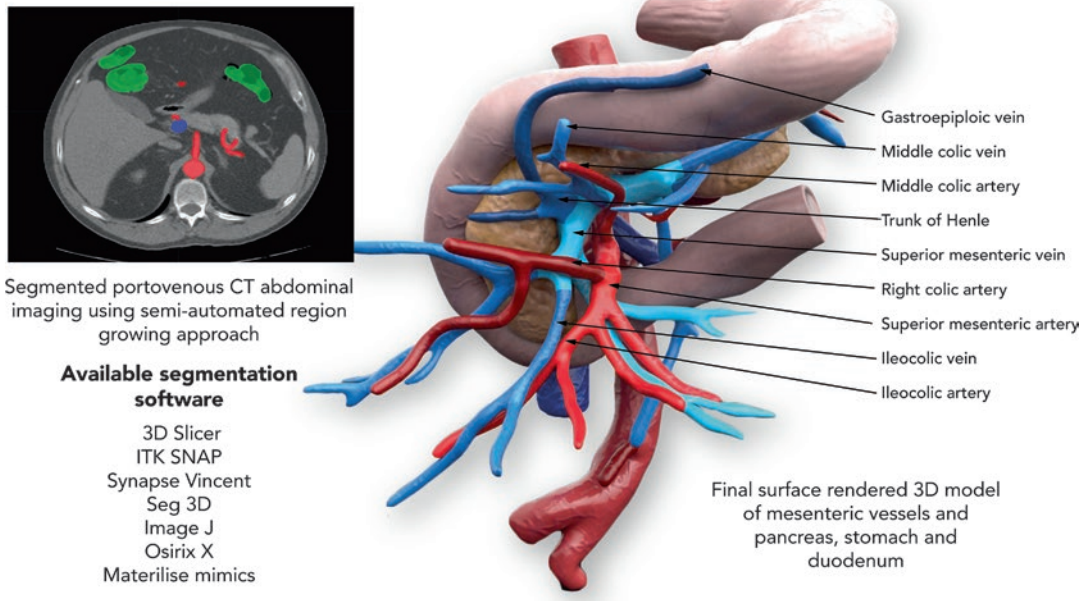


Fig. 8.1 From image segmentation to surface-rendered model – surface-rendered model of mesenteric vascular anatomy derived from CT imaging

number of edges in Euclidean space. Polygonal modeling is an approach for representing three-dimensional objects by approximating their surface structure using multiple polygons (Fig. 8.2).

Surface extraction methods typically rely on binary decisions – for example, whether or not a given pixel in an image slice belongs to the surface. This is appropriate for structures with distinct surfaces, such as bone/ teeth. However, this can produce misleading results when considering non-homogeneous data sets (e.g., abdominal or pelvic imaging), where structures have indistinct boundaries. It is common to see a “staircase” or “stepping” effect especially as the distance between imaging slices increases (this is especially evident with MRI imaging). Most models produced with this workflow therefore require some processing.

Original advantages such as faster render times, a consequence of reduced memory requirements in comparison to volume-rendered models, are less relevant today – due to advances in the capacity of graphical processing units (GPUs). However, surface rendering continues to be an important technique in medical visualiza-

tion with other potential advantages being as follows:

1. Simplicity of interactive visualization on web or mobile platforms, due to lower memory requirements
2. Surface mesh models are required for 3D printing (see below)
3. Biomedical virtual simulation using computer game engines requires surface mesh models. Producing deformable models with physical properties that can be “digitally dissected” requires surface mesh objects.
4. The majority of commercial computer graphics software works with surface meshes allowing for advanced model manipulation techniques to be applied (e.g., digital sculpting, division of structures, colorization and transparency, realistic texturing of organs).

Volumetric Rendering

Volumetric rendering, also termed *direct volume visualization*, represents the original data set without the requirement of the intermediate rep-

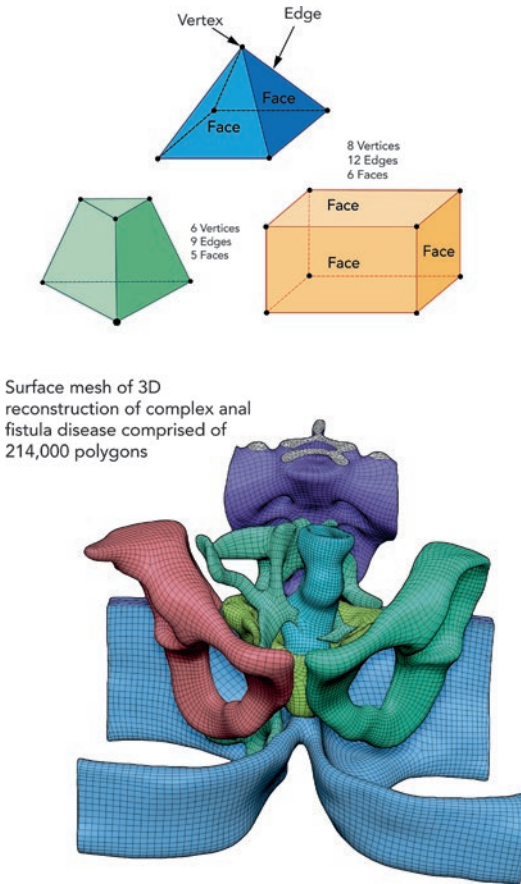


Fig. 8.2 Surface-rendered polygon 3D models composed of vertices, edges, and faces

resentation. Data is visualized as sampled functions of the 3D volume data that are projected as semitransparent volumes onto the 2D viewing plane (Fig. 8.3).

Without the requirement of segmentation, the method preserves all information contained in the image volume. By classifying the values of the contributing structures of the volume and assigning visual properties such as color and transparency, surfaces can be discerned in the rendered image.

3D Printing

The rapid development of 3D printing technology in recent years has created new possibilities in surgical planning and education. Dramatic

reductions in cost along with improvements in the accuracy have facilitated production of patient-specific anatomical printed models.

3D printing or additive manufacturing with rapid prototyping was originally described in the 1980s and is based on the principle of sequentially layering material in order to construct a physical object. Each layer of material will be of equal thickness which varies between machines and techniques – the smaller the layer height, the greater the accuracy or resolution of the model.

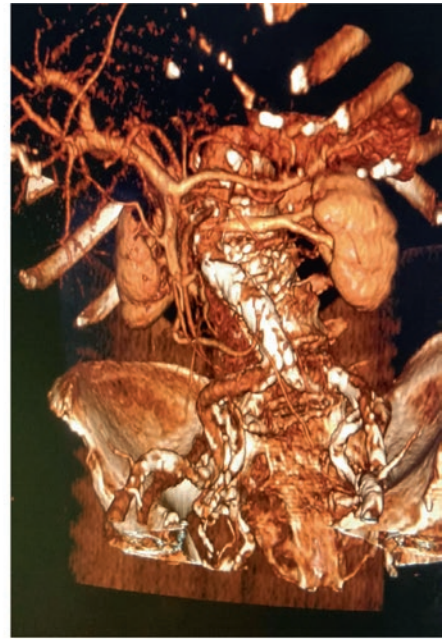
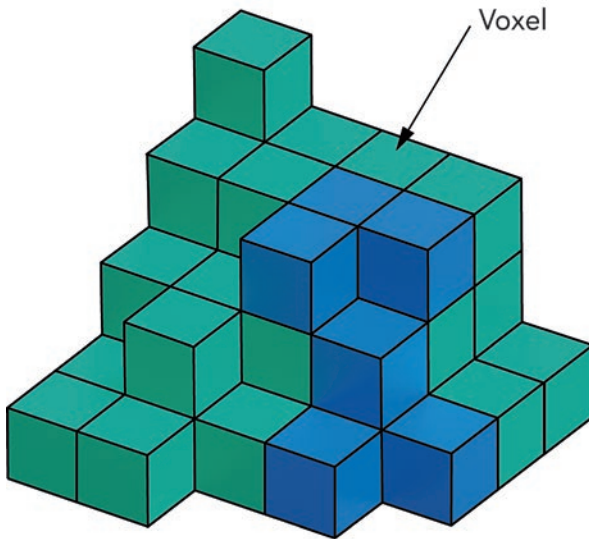
The first steps in creating a 3D printed model from DICOM data are synonymous with the process outlined above for creating a 3D surface mesh. The area of interest must be segmented and subsequently exported as a stereolithography (STL) file – the most widely used file format in 3D printing. However, the raw segmented mesh data will likely need processing in order to be optimized for 3D printing.

Basic smoothing algorithms can be applied to the model to correct minor surface irregularities (e.g., secondary to the “stepping” artifact). A side effect of smoothing can be a loss of resolution. Care must be taken to not grossly distort the original anatomy. More advanced techniques can be used to divide objects into separate components, complete incomplete mesh structures, and perform “digital sculpting.” Such manipulations can be achieved with most commercially available computer graphics modeling software – however, this requires a degree of expertise, with a steep learning curve commonly observed for novices.

3D Printing Methods

There are three main methods of 3D printing commonly used:

1. Material extrusion
 - Fused deposition modeling (FDM)
 - Fused filament fabrication (FFF)
2. Powder solidification
 - Selective laser sintering (SLS)
 - Binder Jetting (BJ)
3. Photosolidification



Volume rendered CT
abdominal imaging

Fig. 8.3 Volume-rendered models. Each voxel represents a point on a regular three-dimensional grid. Their positions/coordinates are not explicitly encoded in their values but are instead inferred from their position to other voxels.

- Stereolithography (SLA)
- Polyjet (PJ)
- Digital light processing (DLA)

Material extrusion is the most common technique utilized by commercially available desktop 3D printers. Material extrusion printers require a continuous filament of “thermoplastic” which is extruded through a heated nozzle. The printer head is precisely moved under computer control using stepper motors, depositing filament on the horizontal plane, one layer at a time to define the printed shape (Fig. 8.4). They are widely used due to their low cost and ease of setup. However, drawbacks include slow print times, a relative lack of precision (in comparison to other methods), and reliability issues which may limit their clinical utility [6].

Powder solidification techniques, such as SLS and BJ, solidify powdered materials. SLS uses a laser to sinter a bed of powder (form a

In order to render a 2D project of the 3D data set, a camera is defined relative to the volume, and each voxel is defined using an RGBA (red, green, blue, and alpha) transfer function

mass solid by applying heat and pressure, without melting to the point of liquefaction). When the layer is solidified, the build plate lowers and a new layer of powder is added, and the process is then repeated (Fig. 8.5). No support materials are required as the powder bed acts as support. *Binder jetting* similarly uses a powder bed build plate but instead uses a precisely sprayed liquid binder for solidification [25].

Photosolidification uses an ultraviolet light laser controlled with lenses and mirrors in order to cure a VAT of photocurable liquid resin. The build platform is typically inverted and moved up as each layer of the object is fabricated in the familiar layer-by-layer fashion (Fig. 8.6). Photosolidification can rapidly produce highly accurate models of incredible intricacy (ideally suited for printing lattice-like vascular structures). Care needs to be taken to ensure the proper handling of resin which can cause severe contact dermatitis.

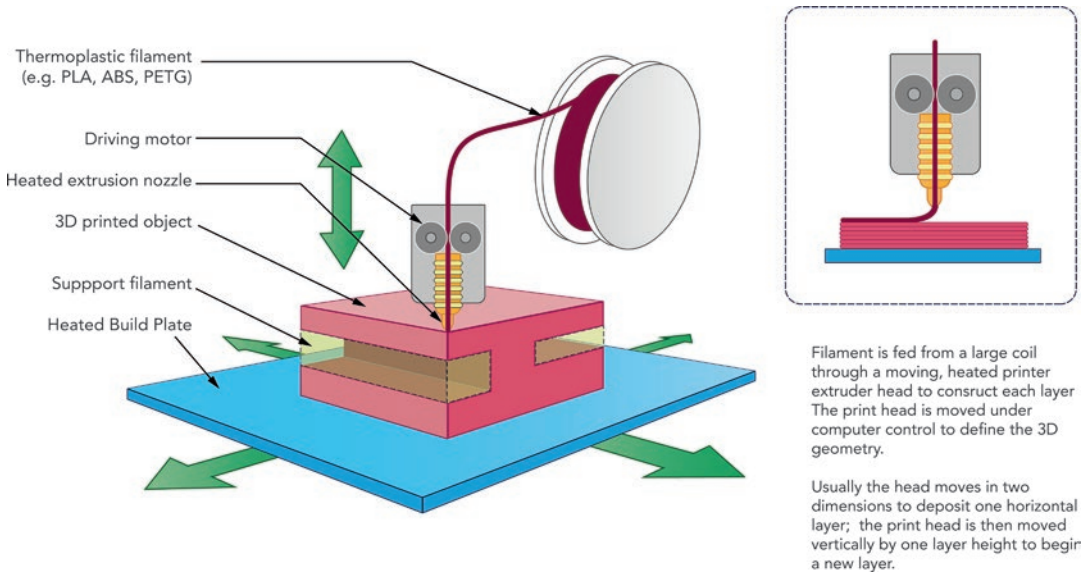
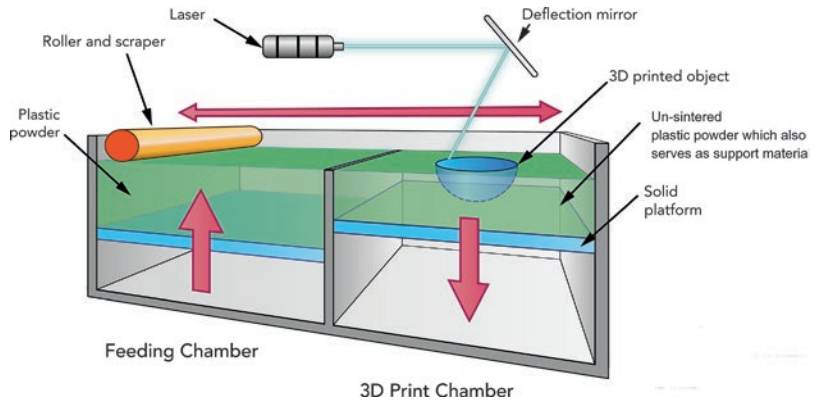


Fig. 8.4 Material extrusion 3D printing

Fig. 8.5 Powder solidification 3D printing. A high-powered laser is used to sinter (fuse) particles of material (plastic, glass, metal). After each layer is produced, the powder bed is lowered, and the roller is used to add new layer of material on top, and the process is repeated



When printing patient models for 3D anatomy, several considerations should be kept in mind. With each method, a degree of technical knowledge is required in order to troubleshoot common mechanical or print errors. This would likely require a dedicated technician or department if printing is to be used in a clinical setting as part of routine care processes [25].

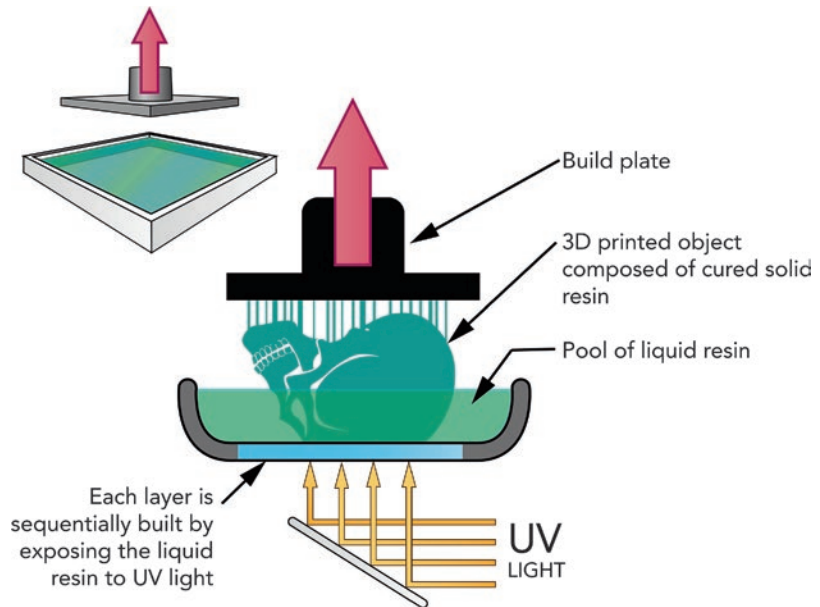
Computer-Assisted Surgery

Computer-assisted surgery (CAS) aims to improve the outcomes and safety of surgical interventions by utilizing digital technologies for

preoperative planning and intraoperative navigation. 3D patient-specific models form an integral aspect of CAS. As discussed above, the workflow begins with image acquisition, followed by higher order processing (segmentation and rendering, etc.) in order to prepare for the visualization stage. It is during this phase that surgical planning occurs as the surgeon interacts with the virtual/physical model in order to gain an appreciation of the specific anatomy and potentially rehearse aspects of the surgery and model outcomes.

This interaction is highly variable in terms of the specific hardware, user interface, type of software utilized, and the planning activity under-

Fig. 8.6 Photosolidification
3D printing



taken. While 2D screen interfaces constitute the principal method of interacting with virtual models, developments in both virtual and augmented realities have allowed for new innovative interface mechanisms.

The resulting plan is subsequently transferred into the operating room. This can be *implicit*, through a mental representation of the case derived from interaction with the model, or *explicit*, through the use of image-guided surgery or mechanical guides (e.g., patient-specific 3D printed cutting guides). The distinction between planning and navigation is increasingly blurred as 3D models are utilized in theater to aid intraoperative navigation through real-time augmented reality interfaces in which the digital image is overlaid onto the operative view. Images can be static, or they can utilize advanced tracking techniques in order to deform the model in synchronicity with real-world tissue manipulations.

3D models have been used in a wide array of planning applications. We can categorize activities of surgical planning into the following general tasks:

1. Improving spatial understanding anatomy and pathology
2. Patient-specific simulation – task rehearsal versus outcome-oriented modeling
3. Resection planning (usually in the context of oncological surgery)
4. Reconstruction planning
5. Implant placement/design

3D and Anatomical Understanding

Anatomical understanding is the baseline requirement on which all surgical procedures are planned and performed. An improved spatial understanding of a patient's anatomy and pathology is a commonly cited advantage of 3D visualization. The task of mentally reconstructing complex structures from 2D imaging slice can be difficult, even for experienced surgeons.

Several authors have examined the effect of 3D virtual models on undergraduate anatomical knowledge acquisition. Azer et al. performed a systematic review on the impact of 3D anatomy models on learning. Of the 30 studies, 60% were randomized controlled trials and the remaining 40% non-randomized comparative studies. 60% utilized objective outcome measures (OSCE, written exam) as opposed to 40% in which subjective ratings were used [26]. Definitive conclusions from these studies are difficult owing to the heterogeneity of methods used and lack of validation for the given outcome measures. Students gener-

ally had a preference for 3D visualization techniques over traditional teaching methods [26]. However, not all studies demonstrated the superiority 3D in comparison to other teaching methods. An important observation of this work was to recognize that multiple factors interact to influence the effectiveness of 3D models on learning. These include 3D model and interface design, cognitive load and task complexity, factors related to the learner (e.g., innate visual-spatial ability), and integration of 3D tools into a wider curriculum.

Few authors have compared the effectiveness of virtual and printed models. Kong et al. found that both virtual and printed models enabled superior understanding of hepatic segment anatomy in comparison to traditional atlas-based training but found no difference between the two 3D groups [27].

Relatively fewer studies have evaluated the effect of 3D models on surgeon anatomical understanding. Awan et al. found the use of 3D printed models of acetabular fractures during a formal training program improved radiology trainee's short-term ability to identify fracture subtypes [28]. Yang et al. evaluated the effect of 3D printed models on the understanding of a retroperitoneal tumor anatomy for medical students, trainees, and consultant (attending) surgeons. When asked to identify three vascular structures, 3D printed and virtual models both demonstrated superiority over MDCT (83.33, 73.33, and 46.67%, respectively, $P = 0.007$), with maximum benefit derived from student group [14].

3D visualization techniques are thought to be of maximum benefit when considering complex variable anatomy. Cromeens et al. tested the ability of pediatric surgeons ($n = 21$) to identify anatomy, understand point-to-point measurements, and the shape and scale in pygopus twins using conventional CT versus virtual reconstructions versus 3D printed models. 3D printed models statistically increased understanding of shape, scale, and anatomy in a significantly quicker time in comparison to MDCT [13].

Patient-Specific Simulation

We can broadly classify simulation using 3D patient-specific modeling into two groups: (a) *process simulation* and (b) *outcome simulation*.

In *process simulation*, the model is used either virtually or physically to recreate the entire procedure or steps of the procedure. *Outcome simulation* attempts to predict operative outcomes and impact of surgery for patients. This can include predictions on the aesthetic appearance post-reconstruction, blood flow, or organ function [21].

Process Simulation

Surgical education has undergone a paradigm shift in recent decades as learning has transitioned from the operating theater to the simulation lab. Reduced operative volume, the need for competency-based curriculum, and patient safety concerns have accelerated this transition. Surgical simulation enables trainees to practice and rehearse skills in a safe environment. This may be especially important for complex, infrequently performed procedures.

Simulation can encompass a wide range of techniques and activities; however, perhaps one drawback of existing training models is their generic nature that lacks the anatomical variation found in real patients [29, 30]. 3D modeling has opened the possibility of patient-specific rehearsal. Imaging data can now be used to generate virtual and physical models in which a trainee or surgeon can perform key operative steps before carrying out the actual operation on a real patient. When considering the link between deliberate practice and expert performance in a wide range of fields such as sports, board games, and music, patient-specific rehearsal offers great promise in improving operative performance and safety [31, 32].

3D Printing and Simulation

The ability to print accurate scale models of bony anatomy (Fig. 8.7) has enabled surgeons from a variety of specialties to rehearse aspects of trauma and reconstructive surgery. Surgeons have used these printed models to design and perform osteotomies, prebend, and apply osteosynthesis implants. Head and neck surgeons have used such methods extensively to simulate complicated mandibular and other complex facial reconstructions [33–35]. Authors commonly cite reduced operative times, improved accuracy, and superior aesthetic results as the key benefits [8].

The hard materials used by the majority of 3D printers limit their use for simulation of procedures involving soft organs. However, soft flexible materials can now be printed, and hard 3D prints can be used to make silicone molds for traditional casting techniques.

Coelho et al. recently developed a 3D printed model with multiple materials of varying consistencies and resistances for planning frontoethmoidal meningoencephalocele surgical correction. Aside from reducing operative time by an estimated 29%, the model facilitated multidisciplinary discussion between neurosurgeon and plastic surgeons allowing alterations of the previously defined plan [36].

Initial feasibility studies for simulating nephrectomies with patient-specific 3D printed models have been undertaken. Glybochko et al. evaluated patient-specific silicone models for five patients with renal cell carcinoma. Surgeons rated the models highly for fidelity, and, subjectively, the models enabled better evaluation of the tumor anatomy [37]. Von Rundstedt et al. similarly generated patient-specific soft models for preoperative rehearsal for ten patients with com-

plex renal tumor anatomy. Construct validity was demonstrated by similar enucleation times and resected tissue volumes between the model and actual tumors. Authors felt such rehearsals impacted their operative approach as difficulties encountered during the simulation *significantly altered the approach to the tumor in several cases* [15]. Cheung et al. used a three-stage production process to develop and validate a pediatric laparoscopic pyeloplasty. 3D organs based on imaging data were used to create 3D printed molds for subsequent silicone casting. During initial validation at the Canadian Urological Association, both trainee and expert users rated the models 4.75 (out of 5) for overall impression, 4.50 for realism, and 4.38 for handling [38]. Although promising, these early studies lack any clear objective assessment of utility or transferability into theater. Further drawbacks relate the time and expense incurred, with models taking up to 5 days and \$450–\$1000 to produce.

Virtual Patient-Specific Simulation

Given the material cost and infrastructure required for physical model production, virtual simulation is desirable. However, generating patient-specific realistic procedural simulations based on imaging-derived 3D models remains a significant challenge.

Models must undergo complex post-segmentation processing in order to be optimized for a game engine – the software development environment used in video game development that enables realistic rendering and physics to be applied to 3D models.

Creating deformable models with real-world physical properties that the user can interact with and dissect would not only be costly and time-consuming but also require a team with advanced computer programming knowledge [39].

Currently, only a handful of early feasibility studies are available. Rai et al. utilized Mimics (Leuven, Belgium) 3D virtual simulation environment in order to simulate three partial nephrectomy cases using CT reconstructed models [16]. Other preliminary studies by head and neck surgeons developed a virtual surgical environment for simulating ten endoscopic skull base



Fig. 8.7 1:1 scale FDM 3D printed sacrum derived from CT data (print material PLA, print time 34 h)

procedures, demonstrating sufficient realism to allow patient-specific rehearsal [40]. Despite the obvious difficulties posed by virtual patient-specific simulation, the potential benefits for surgical training and patient safety are enormous and should therefore be a research priority in surgical education and training moving forward.

Outcome Simulation

Outcome simulation attempts to predict the result of surgery. We encounter four main types of outcome simulations in the literature: aesthetic, motion, blood flow, and structural. As discussed in further detail below, aesthetic outcomes are especially important in plastic and oral maxillofacial surgery. Computer modeling using finite element methods can accurately predict the soft tissue changes following bony reconstruction of the mandible and hence the resulting facial appearance [41]. The anticipated range of motion can similarly be modeled after orthopedic implants. This can facilitate decision-making, as real-time feedback is provided as different implants and placements are virtually trialed [42].

With virtual stenting, postoperative blood flow patterns can be modeled. This can be crucial when planning interventional procedures, e.g., aneurysm repair. The pressure and wall stress following stent placement can be predicted, meaning placement can be optimized [21]. Orthopedic surgeons use algorithmic approaches to predict the structural integrity of an implant and anatomic embedding. Surgeons can now visualize the forces and stresses on implants in order to optimize configurations [43].

Resection Planning

Achieving R0 (tumor-free) resection margins is the primary objective of curative oncological surgery and is one of the most important predictors of long-term survival [44].

Surgical planning involves interpretation of 2D CT/MRI imaging in order to mentally reconstruct the tumor anatomy and relationships to surrounding structures. 3D modeling may be

especially beneficial when planning complex resections, given the potential for improved anatomical understanding that may subsequently impact decision-making and operative performance. One of the challenges of this surgery lies in removing sufficient tissue to ensure tumor-free margins while preserving enough tissue to avoid post-resection liver failure. Identification of vascular tributaries is fundamental aspect of plan in order to preserve healthy liver. Hepatobiliary surgeons have used 3D reconstructions in planning liver resections for primary and secondary liver cancer [45].

Tian et al. virtually simulated resection of tumors, demonstrating accurate predicted values for the specimen volume and surgical margins using the technique [46]. Wang et al. examined the effect of 3D visualization and virtual resection on surgical planning in comparison to 2D imaging on 305 consecutive patients undergoing hepatectomy. 3D visualization was found to alter the intended surgical plan for complex hepatectomy patients in 49/131 cases; *notably, 15 patients deemed unresectable based on 2D DICOM data were reconsidered operable*. The virtual resection volumes similarly correlated with the eventual specimen volume [47].

Virtual 3D analysis of hepatic tumors enabled accurate identification of tumor-bearing vasculature and perfusion areas essential for anatomical segmentectomy. Furthermore, by combining perfusion data with virtual resections, surgeons can automatically be provided with resection volumes, functional liver reserve, and dysfunction volumes, all critical information when planning the feasibility of hepatectomy. However, not all studies demonstrated 3D had any benefit. For example, Andert et al. found no difference between the R0 resection rates for hilar cholangiocarcinoma for 3D ($n = 17$) versus non-3D ($n = 16$) planning methods [48].

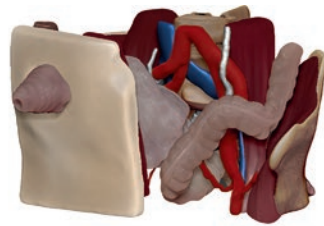
Video-assisted thoracotomy (VATS) lobectomy is a lesion-oriented procedure requiring a clear understanding of the pathology in relation to the complex distribution of blood vessels and bronchi. Consequently, thoracic surgeons have utilized 3D reconstructions for planning minimally invasive pulmonary resections [49, 50].

Similar preliminary work has been conducted in planning partial nephrectomy for renal cell carcinoma, complete mesocolic excision for colonic cancer [12], and complex sarcoma resections [51]. While 3D was considered to be useful and beneficial to operative performance, these studies are characterized by subjective findings lacking comparators, thus precluding any firm conclusions. At St. Mark's Hospital (London, UK), we have performed initial feasibility work assessing 3D reconstructions for planning locally advanced rectal cancer exenterative surgery (Fig. 8.8).

Reconstruction

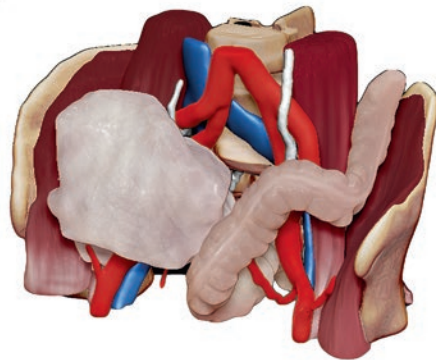
Oral maxillofacial surgery (OMFS) serves as one of the best examples of using 3D modeling for planning reconstructive surgery. OMFS primarily deals with the reconstruction of the bones of the facial area following trauma or to correct congenital malformations [52]. Not only is craniofacial anatomy geometrically complex, but deformities are also exceptionally visible and carry a considerable psychosocial burden for patients. The precision and aesthetic requirements of procedures are therefore particularly

Fig. 8.8 3D surface-rendered reconstructions of two complex colorectal cancer patients requiring exenterative surgery

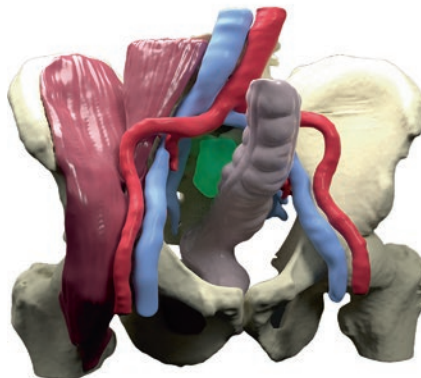


Advanced necrotic caecal tumour encasing the iliac vessels and right ureter, invading the right ileopsoas muscle and adherent to the sigmoid

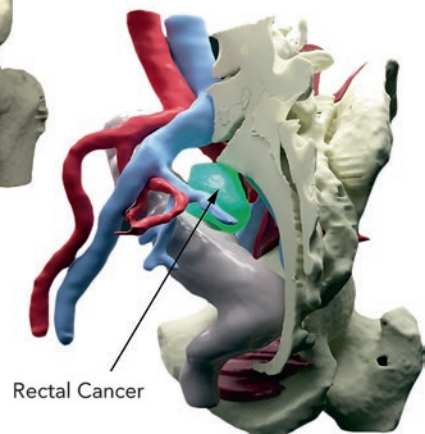
Case 1



Case 2



Advanced rectal cancer invading S1 requiring exenterative surgery



Rectal Cancer

stringent. 3D imaging potentially has its biggest impact where correction of defects is essential for functional and cosmetic outcomes.

3D visualization techniques have been used not only to improve understanding of the deformity but to also accurately plan osteotomies, virtually/physically rehearse reconstructive techniques [52], accurately model the soft tissue postoperative appearances [53], and 3D print patient-specific cutting guides and custom implants [54]. Such measures have enabled quicker surgery with improved precision and aesthetic outcomes [55, 56].

In facial trauma, the spatial localization of bone fragments is essential in restoring the shape of the face and normal bite. 3D CT enables planning symmetrical corrections along with placement of implants. Several studies have demonstrated the value of 3D CT visualization in the treatment of displaced complex midfacial and mandibular fractures [54, 57, 58].

3D has also demonstrated value in the evaluation and treatment of craniofacial clefts, synostoses, and other asymmetries. In craniosynostosis – a condition in which the cranial suture closes prematurely changing the growth pattern of the skull – 3D CT is more likely to reveal subtle asymmetries and result in more accurate classification of abnormal suture lines [59]. 3D printing also provides a useful means of simulating surgery, particularly through planning and performing osteotomy sites.

In one review, Lin et al. identified 78 studies in the past decade that have employed 3D printing to transfer virtual planning to actual orthognathic reconstructions (methods include occlusal splints, osteotomy guides, repositioning guides, fixation plates/implants, spacers, and 3D models) [60]. The majority of studies were prospective case series ranging between 1 and 150 patients (with a median of 10) using accuracy as primary outcome measures.

Significantly fewer randomized controlled trials have been undertaken. Ayoub et al. compared computer-assisted mandibular reconstruction with vascularized iliac crest bone grafts with conventional surgery with a total of 20 patients randomized into each group.

Computer-assisted surgery reduced the transplant ischemia time and reduced the donor site defect size [61].

Discussion

3D modeling is an emerging technology that will likely gain increased prominence within surgical workflows in the next decade. Patient-specific modeling offers not only the potential for improving anatomical understanding but also novel ways of interacting with imaging data. Proponents hope the use of such models will facilitate the delivery of precision medicine and result in safer, faster surgery with better outcomes.

However, the effectiveness of 3D virtual or printed models remains to be definitively established. Considerable technical challenges remain if 3D modeling is to be integrated into routine care. The surgical community will likely need to partner with industry if model production is to be automated.

We have yet to elucidate the ideal user (novice versus expert), specific indications, optimum design, and interface features. The majority of the current literature consists of small-scale feasibility studies in which only subjective measures of utility are employed. Future research must address these questions and establish adequate methodology in order to validate 3D modeling as an effective adjunct to preoperative planning.

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