

From CT scanning to 3-D printing technology for the preoperative planning in laparoscopic splenectomy

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Abstract

Background Three-dimensional printing technology is rapidly changing the way we produce all sort of objects, having also included medical applications. We embarked in a pilot study to assess the value of patient-specific 3-D physical manufacturing of spleno-pancreatic anatomy in helping during patient's counseling and for preoperative planning.

Methods Twelve patients scheduled for a laparoscopic splenectomy underwent contrast CT and subsequent post-processing to create virtual 3-D models of the target anatomy, and 3-D printing of the relative solid objects. The printing process, its cost and encountered problems were monitored and recorded. Patients were asked to rate the value of 3-D objects on a 1–5 scale in facilitating their understanding of the proposed procedure. Also 10 surgical residents were required to evaluate the perceived extra value of 3-D printing in the preoperative planning process.

Results The post-processing analysis required an average of 2; 20 h was needed to physically print each model and 4 additional hours to finalize each object. The cost for the material employed for each object was around 300 euros.

Ten patients gave a score of 5, two a score of 4. Six residents gave a score of 5, four a score of 4.

Conclusions Three-dimensional printing is helpful in understanding complex anatomy for educational purposes at all levels. Cost and working time to produce good quality objects are still considerable.

Keywords Laparoscopic splenectomy · Intraoperative navigation · Computing · CT of the spleen · Surgical education · 3D printing

Computer-based digital imaging technology has become a fundamental part of today's surgery through its integration at all levels of surgical care. The progressive shift from traditional two-dimensional (2-D) imaging to the 3-D visualizations, available through such technologies as CT or MRI scanning and virtual reality, has offered effective new tools for preoperative diagnostics and planning as well as for intraoperative navigation [1]. More recently, 3-D printing has changed the way we produce objects, from tools and toys [2] to food [3], even body parts [4]. This technical revolution is taking place across almost every sphere of human action. The sense of touch is of major importance in the perception of three-dimensional shapes [5]. The interpretation of complex surgical anatomy from existing diagnostic technology still represents a challenge for surgeons. We designed a pilot study to assess the potential value of 3-D printing technology as a new method to physically manufacture patient-specific anatomical objects, to be used as a substitute for conventional 3-D virtual reconstructions. As a preliminary model, the setting of preoperative planning in laparoscopic splenectomy was considered in this report.

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Materials and methods

Generation of 3-D objects

The manufacturing of 3-D objects starts from the acquisition of saved images in the Digital Imaging and Communications in Medicine (DICOM) format generated by a multi-detector computed tomography (MDCT) scan. Since the final rendering of the 3-D spleno-pancreatic block depends on the quality of the data, it is important to use high-quality contrast images with slice thickness of at least 2 mm. Images are acquired during the arterial contrastographic phase. This proved to be the best option since it simultaneously allowed for optimal visualization of spleen parenchyma, pancreatic tail and splenic artery and vein, including their branching. Each anatomical structure is seen during this phase with different contrast levels, thus allowing a selective identification of each of them in the post-process analysis. Post-processing images are based on segmentation, in order to generate the 3-D virtual model of the considered anatomy. Segmentation is the process of labeling each structure of interest in each MDCT slice. This operation was achieved through open source software, ITK-SNAP (<http://www.itksnap.org>) [6], that implements a semiautomatic procedure based on a simple region-growing algorithm. The segmentation process of each structure starts from the definition of a gray level window including all the gray shades of the structure of interest. The second step is to define one or more starting points on the images, which are the spherical surfaces from which the algorithm will start its evolution (Fig. 1A). The algorithm grows within each MDCT slice and throughout the slices (Fig. 1B). The evolution is based on various parameters, including the expansion factor that controls the forces acting inwards and outwards from the surface and the curvature factor that controls how the 3-D surface is able to lose its sphericity and adapt to image details. When the algorithm has completed its evolution, the resulting label set is rendered to produce a 3-D surface (Fig. 2). The

virtual model is navigable, and the user can interact with it, changing the transparency or the false color of each structure in the 3-D rendering, as well as creating a detailed view of the interaction among the different anatomical structures. After post-processing, the Surface Triangulation Language (STL) representation of the 3-D surface is exported directly from the ITK-SNAP software to the 3-D printer. The STL is a description of the object's complex geometry obtained through an approximation, by a series of oriented triangular facets. The smaller the triangular areas, the smoother the surface will appear. It is the most common input format used by 3-D printers. The physical additive manufacturing was realized with an Object 30 Pro 3-D printer (Stratasys Ltd. ©). Powered by PolyJet technology, the Object 30 Pro 3-D printer offers eight different 3-D printing materials, featuring the industry's best print resolution, with a capacity to lay down layers of material up to 16 microns in thickness. The printer's roomy tray size, which corresponds to the maximum size of printable objects, is of $300 \times 200 \times 150$ mm. To build our models, we used white, rigid photopolymeric material and a support material. The support material was easily removed after printing with a water-jet cleaner. Each part that was extracted during the segmentation process (spleen, splenic artery, splenic vein, pancreatic tail) was separately printed, using a white, rigid material. Then, each part was painted using aniline dye color and finally assembled with glue to reconstruct the final graspable object (Fig. 3).

Patients and methods

Since January 2014, we produced anatomical objects of surgical patients in 18 cases: 1 cancer of the head of the pancreas, 5 kidneys to undergo either partial nephrectomy for cancer (2 cases) or total nephrectomy for living donation (3 cases) and 12 spleno-pancreatic models. The series of 12 patients scheduled to undergo a laparoscopic splenectomy represented the object of the present pilot study. A minimally invasive technique, either pure

Fig. 1 A, B Segmentation procedure. Starting surfaces for spleen segmentation (A) and final result on a MDCT slice (B)

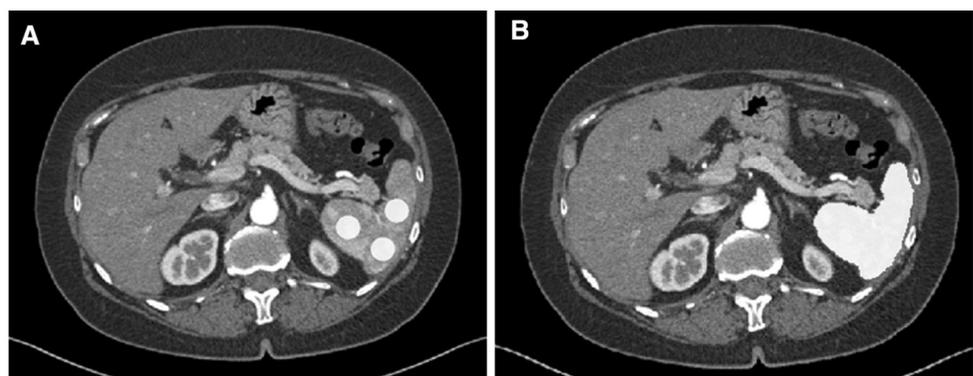


Fig. 2 3-D rendering of the segmentation result. The model includes the spleen, the splenic artery and vein and the tail of the pancreas

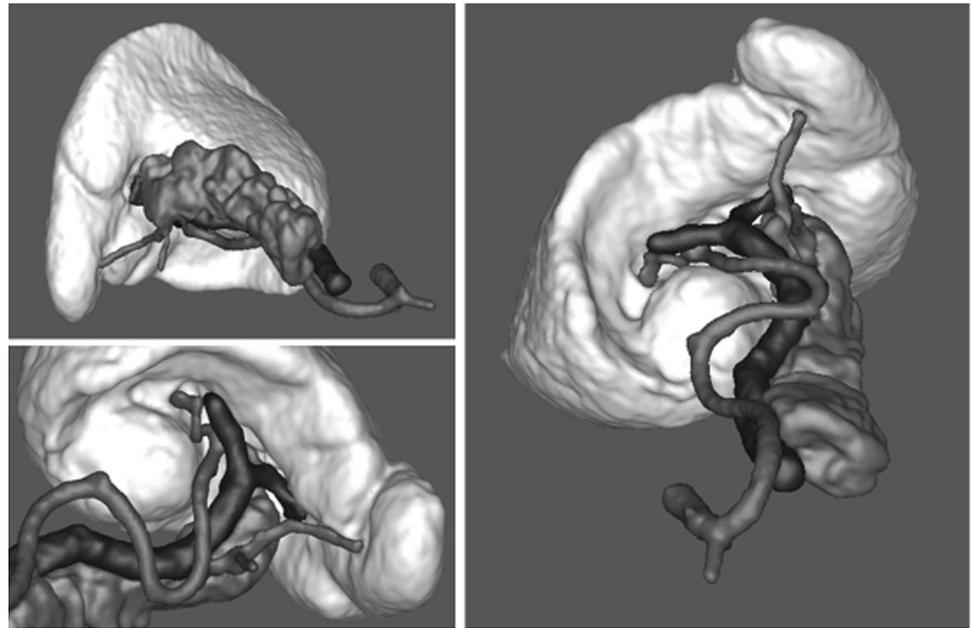


Fig. 3 3-D printed model of the spleen after painting and assembly. The printer is able to reproduce even the small vessels and the finest details

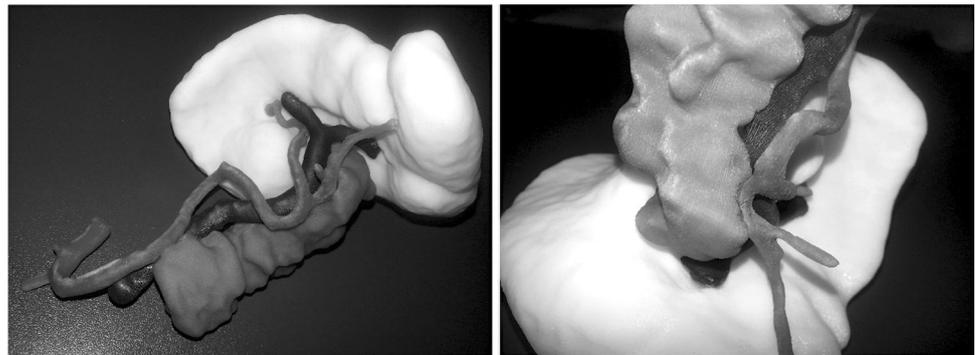


Table 1 Patients data, type of surgical approach and outcome

PT #	Age	Sex	Max diameter (cm)	Disease	LAP/HALS	Op time (min)	Conversion (Y/N)	P. O. stay (days)
1	67	M	13	Lymphoma	LAP	95	N	3
2	71	M	17	Lymphoma	HALS	60	N	3
3	65	F	22	Lymphoma	LAP	104	N	5
4	62	F	11	ITP	LAP	70	N	9
5	68	F	24	Lymphoma	HALS	95	N	10
6	66	F	9	ITP	LAP	50	N	4
7	45	M	20	Lymphoma	HALS	135	N	8
8	61	M	10	ITP	LAP	40	N	5
9	42	M	23	Lymphoma	HALS	200	N	6
10	54	M	22	Lymphoma	HALS	180	N	5
11	72	F	9	Splenic artery aneurysm	Robotic	160	N	4
12	45	M	15	ITP	LAP	75	N	4

laparoscopic or hand assisted was planned in all patients. Patient's data are shown in Table 1. The time and the estimated cost related to the manufacturing of each 3-D model were recorded. Problems encountered during the post-processing phase or the 3-D printing were also monitored and recorded. The 3-D models of the spleen and its vascular anatomy were used during the preoperative counseling with the patient and his/her family, to help clarify the type of procedure planned and its potential complications. Patients were allowed to handle the models and asked to anonymously rate the extra value provided by the new tool in facilitating their understanding of the proposed treatment on a scale of 1–5 (1 = no extra value; 5 = very high extra value). The models were also used during the preoperative briefings with surgical residents who were about to attend the operation. Again, they were asked to rate on scale of 1–5 the usefulness of the new tool in helping their understanding of the surgical anatomy and of the various steps of the planned procedure.

Results

The post-processing work of reconstruction, consistently validated by a radiologist to provide the complete virtual model of the anatomical structures of interest, required about 2 h of commitment on the part of a PhD student. Despite the commonly used term “rapid prototyping,” the printing process of the physical object took on average 20 h; however, since the printing process requires no active control from the user, we usually let the printer run also overnight. In addition, it took about 4 h of manpower of a dedicated PhD student to complete each object, including water-jet cleaning, the final painting and glue assembling. The cost of the printer was of roughly 50,000 euros, with an additional cost of consumables to manufacture each model of about 300 euros. In this pilot study on spleen anatomy, thanks to the relatively small area of interest, we were able to build full-size objects. When the spleen was too large to fit within the printing area, we restricted the printing process to the hilum of the spleen and to a minimum amount of splenic parenchyma. The very thin layers of printing material allowed the printer to reproduce even the smallest of anatomical details, approximating the detail resolution capability of the CT scanner that we used. Thus, any loss of anatomical information during the generation of 3-D objects was negligible for our purposes.

Patients and their families consistently enjoyed the opportunity to see and handle the anatomical models, which invariably provided the basis for additional questions and discussion on the planned procedure and its technical details. The relative rating was 5 (very high value) in 10 cases and 4 (high value) in 2. In general, the

new tool seemed to enforce the patient's comprehension of the type of operation as well as his/her confidence in the surgeon. Our residents also found the 3-D objects useful for their understanding of the surgical anatomy and of the technical steps of the planned laparoscopic procedure. Out of 10 residents involved in the study, 6 scored the models as 5 (very much useful), the remaining 4 as 4 (very useful).

Discussion

One of the most important skills that must be developed by surgeons is the spatial reconstruction and integration of 2-D images provided by medical imaging within the real anatomy of the patient. Surgeons generally view these images (mostly CT or MRI) on 2-D monitors. Using a number of these image slices, surgeons build their own mental 3-D model of the anatomy of interest and of the pathology they are committed to treat. This process is based on their previous experience in “mental imaging,” combined with sound anatomical knowledge. The latter is continuously re-enforced by the intraoperative feedback provided by the real anatomy of each case undergoing surgical treatment. Therefore, the mental reconstruction of a surgeon is likely to differ from that of other medical doctors who miss the above-mentioned source of information. In addition, surgeons should also be able to reconstruct in their mind how different information provided by the available imaging tools (CT, MRI, US, PET) is spatially interconnected. This process of fusion can also be challenging, even for the most experienced surgeon, due to the inter-individual anatomical variation and to the distortion induced by the disease. In surgery, the ability to mentally generate, maintain, transform and recognize structures is critical for success. Moreover, the capability to arrange a mental reconstruction of a patient's anatomy is of particular value when planning a laparoscopic procedure. In consequence of the limited intraoperative anatomical exposure and partial loss of tactile sense in laparoscopic surgery, intraoperative decisions rely mostly on preoperative images. This is especially the case as compared to open surgery. Due to the complexity of this reconstructive process, which largely depends on experience, young surgeons can miss important information or draw incorrect conclusions that can lead to suboptimal treatment. The tortuous course of the splenic artery is extremely variable, and no two arteries are alike. In about one-third of individuals, the splenic artery divides terminally near the spleen. This pattern of division is called a magistral splenic [7]. When the division of the splenic artery occurs earlier, as in the remaining two-thirds of individuals, it is called a distributing splenic. Preoperative recognition of the patient's pattern of branching of the splenic artery is of

surgical relevance, since one of the most important operative steps of a laparoscopic splenectomy, particularly in the case of an enlarged spleen, is the early ligation of the splenic artery before its branching to achieve a complete devascularization. This reduces the size of the organ, allowing for a sort of autotransfusion and limiting the adverse consequences of inadvertent breaching of its capsule that might occur during the dissection [8]. A preoperative knowledge of the pattern of division of the splenic artery and of its course in relation to the pancreatic tail is therefore desirable to help in choosing where to dissect the artery off the pancreatic tail and ligate it. Nonetheless, full understanding of this information after simple scrolling of 2-D MDCT image slices is very difficult, even for the experienced surgeon. To overcome this problem, 3-D virtual reconstructions have been used to maximize understanding of the anatomy and increase the accuracy of the surgeon [9]. However, radiologists and surgeons are generally restricted by the use of flat screens for the visualization of 3-D images. In this setting, the true sense of depth is limited and for this reason artificial motion should be added to the reconstructed images. By rotating the angle of view, the anatomical relationships of different structures is better understood, increasing recognition errors, and thus some sense of depth [10]. Obviously, the use of 3-D information is limited to the availability of a computer with access to patient data and with a dedicated program of image processing and display. This can be impractical for the purpose of helping the patient's knowledge of his/her disease during counseling, or for the trainee's preoperative understanding of the intended operation, as well as to assist the surgeon during the operative procedure. In any case, 3-D vision cannot replace the 3-D physical information that can be gained by exploring an object with one's hands [11, 12]. In the real world, the recognition of peculiar features, such as geometrical shape and surface texture, is performed by exploratory procedures of hands and fingers, which are actively controlled by the subject [13]. The perceptual system devoted to the recognition of such features is called haptic perception [14]. The sensory information exploited by the haptic system for the recognition of real objects is kinesthetic and cutaneous inputs. While kinesthetic inputs refer to the perception of the spatial configuration of the hand and fingers, the cutaneous inputs deal with the perception of the contact conditions between the human hand and the real object. [15]. Vision and touch generate functionally overlapping, but not necessarily equivalent, representations of 3-D shape. Experimental evidence suggests that haptic exploration can influence and improve visual perception of 3-D shape [16, 17].

In recent years, 3-D printing technology, also known as additive manufacturing, has been increasingly used by industries from aerospace and consumer electronics to

biological applications [18]. Thanks to its ability to make customizable objects with no additional tooling or material waste, the process, which involves a machine layering materials to make an object from a digital model, has been suggested for its use in medicine and surgery [19, 20]. Imaging data sets of a given patient, usually extracted from CT scanning, are utilized by the 3-D printer to create graspable objects of the anatomy of interest. Complex anatomical relationships can be better appreciated on 3-D solid models "in hand" rather than on 2-D or conventional 3-D visualization tools. Touch seems to recalibrate the visual perception so that it is better able to infer depth from the retinal projection. Recently, 3-D printing has been proposed for the preoperative planning of live-donor hepatectomies and for nephron-sparing surgery [21, 22].

We reported our preliminary experience with 3-D printing technology for preoperative planning in a select group of candidates for laparoscopic splenectomy. Although the highest value of 3-D printed anatomical objects in general surgery will likely result in providing a new tool for the surgical planning of complex procedures, such as major hepatectomies, nephron-sparing surgery or pancreatic resections, in this report we chose a more simple setting, mostly to demonstrate the feasibility of the manufacturing process, its current drawback, and to show the additional value of the 3-D object as a teaching tool. The preoperative counseling with the patient and his/her family is a valuable opportunity to set realistic expectations regarding the extent of surgery and discuss possible complications [23]. Often this can make the patient more confident when he or she enters the operating room. The availability of a real size 3-D model of the patient's own spleen and its vessels proved very useful in explaining the steps of the planned laparoscopic procedure and the reasoning behind possible complications. Throughout this study, patients liked the opportunity to hold in their hands the anatomical models, rating its additional value very highly in almost every instance. Also our residents consistently appreciated the 3-D physical reconstruction and the help it provided during the preoperative briefing in understanding the procedure and anticipating its various steps. Although all the surgeons involved in the present study seemed to appreciate the availability of the 3-D anatomical models, additional studies will be needed to assess the real advantage of this technology over conventional anatomical representation, also for the experienced surgeon.

In our experience, the main drawback of current 3-D printing was the cost of production and the significant hours of specialized staff needed to actualize the model. However, as the cost of 3-D printing technology declines and semiautomatic protocols are developed for the reconstruction of 3-D virtual models [24, 25], it is easy to

imagine that additive manufacturing production of anatomical objects may become affordable and worth doing for many scenarios in general surgery. Although the 3-D printing of anatomical objects is currently an undeveloped field, we believe that it might soon become a relevant topic in medicine, opening new areas of research in surgical education.

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