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REVIEW ARTICLE

An overview on 3D printing for abdominal surgery

Andrea Pietrabissa[1,2] · Stefania Marconi[3] · Erika Negrello[1] · Valeria Mauri[1] · Andrea Peri[1] · Luigi Pugliese[1] · Enrico Maria Marone[1,2] · Ferdinando Auricchio[3]

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Abstract

Background Three-dimensional (3D) printing is a disruptive technology that is quickly spreading to many fields, including healthcare. In this context, it allows the creation of graspable, patient-specific, anatomical models generated from medical images. The ability to hold and show a physical object speeds up and facilitates the understanding of anatomical details, eases patient counseling and contributes to the education and training of students and residents. Several medical specialties are currently exploring the potential of this technology, including general surgery.

Methods In this review, we provide an overview on the available 3D printing technologies, together with a systematic analysis of the medical literature dedicated to its application for abdominal surgery. Our experience with the first clinical laboratory for 3D printing in Italy is also reported.

Results There was a tenfold increase in the number of publications per year over the last decade. About 70% of these papers focused on kidney and liver models, produced primarily for pre-interventional planning, as well as for educational and training purposes. The most used printing technologies are material jetting and material extrusion. Seventy-three percent of publications reported on fewer than ten clinical cases.

Conclusion The increasing application of 3D printing in abdominal surgery reflects the dawn of a new technology, although it is still in its infancy. The potential benefit of this technology is clear, however, and it may soon lead to the development of new hospital facilities to improve surgical training, research, and patient care.

Keywords Three-dimensional printing · Additive manufacturing · Rapid prototyping · Virtual reconstruction · Simulation for surgery

Over time, novel technologies and the introduction of diagnostic imaging have re-shaped the practice of surgery. Today, modern multi-detector computed tomography (MDCT) and magnetic resonance imaging (MRI) systems, in combination with the advances in image processing, allow the generation of detailed 3D virtual models of a patient's anatomy, to support the diagnosis and the planning process of complex interventional management. However, the use of 3D reconstructions is often limited by the lack of a computer platform with access to the patient's data and the absence of dedicated software for image processing and display. That can be impractical for many aspects of its potential use: pre-treatment interventional planning, patient counseling, teaching to students and residents and intraoperative guidance. But with the right tools in place, 3D printing can enable the transition from the virtual world to the real one, providing the tactile feedback of an anatomical model and ensuring its ready availability in any desired setting, including the patient's bedside. Although originally introduced 30 years ago for industrial production as a tool for rapid prototyping, today 3D printing is gaining popularity in many fields, including healthcare, thanks to its ability to reproduce complex geometries, such as that typical of solid organs and major blood vessels. The increasing adoption of 3D printing in a wide range of medical and surgical specialties mirrors the rapid spread of this technology in the global market. Moreover, the creation of a single copy of a patient-specific anatomical

✉ Stefania Marconi
stefania.marconi@unipv.it

1 Fondazione IRCCS Policlinico San Matteo, Pavia, Italy

2 Department of Clinical-Surgical, Diagnostic and Pediatric Sciences, University of Pavia, Pavia, Italy

3 Department of Civil Engineering and Architecture, University of Pavia, via Ferrata, 3, 27100 Pavia, Italy

model is in keeping with the growing personalization of treatment, one of the keys of modern precision medicine.

The underlying technology of every 3D printer is based on the same general concept: the selected object is manufactured through a layer-by-layer process. Initially, the virtual model is divided into thin layers of equal width. Then, each layer is sent to the 3D printer, which deploys its material in the specified sequence. The various printers available on the market differ in the way layers are deposited and cured, according to the type of material employed.

The American Society for Testing and Materials International (ASTM International), an organization that develops and publishes consensus technical standards for a vast array of products and materials, recognizes seven main categories of 3D printers [1], classified by their materials and curing systems:

- *Vat photopolymerization* this process involves the use of a photopolymer resin, hardened by means of a light source. The most common technology is stereolithography (SLA), which uses an ultraviolet (UV) laser to cure the resin layer by layer.
- *Material jetting* this approach resembles that of an inkjet paper printer, where the printing material is dropped through small-diameter nozzles. Base materials are photopolymer resins, hardened by a UV lamp. One of the main advantages of this printing process is the ability to combine several materials, with different colors and varying degrees of transparency and deformability, while maintaining high resolution and performance.
- *Binder jetting* this technique involves the use of two base materials, a chalk powder and a liquid binder. The powder is distributed in uniform layers and the binder is applied through small nozzles to glue together powder particles according to the 3D virtual model. Furthermore, it enables the printing of full-color scale models, thanks to the use of color inkjet cartridges.
- *Material extrusion* this is the most popular and cheapest 3D printing technology available on the market. These printers work using thermoplastic filaments, which are pushed through a heating chamber and extruded through a small nozzle; the melted material is deployed layer by layer, following a path designated by the 3D virtual model. The most common material extrusion technology is fused deposition modeling (FDM—a term trademarked by Stratasys®) or fused filament fabrication (FFF—the open source equivalent term).
- *Powder bed fusion* (best known as Selective Laser Sintering) this technology involves the use of a powerful laser source capable of melting plastic, metal or ceramic powder particles into the desired 3D object. The laser selectively fuses the powdered material by scanning the cross-sections on the surface of the powder bed.
- *Sheet lamination* with this technique, sheets of material are bonded together through external forces; different mechanisms can be employed to achieve interlayer bonding, such as adhesive bonding (e.g., a sheet of paper), thermal bonding, clamping or ultrasonic welding (e.g., sheet metal).
- *Direct energy deposition (DED)* here, 3D-printed components are created by melting a metal powder directly during its deposition. In this process, typically applied in the high-tech metal industry, metal powders or filaments are melted by an energy source (electron beam, laser or plasma arc) and deployed with a great degree of freedom, thanks to machines with up to five axes of movement.

Three-dimensional printing for abdominal surgery is usually related to the creation of physical replicas of a patient-specific anatomical model, but its use can also be extended to the production of surgical instruments or implantable devices. Regardless to the specific medical specialty, a 3D-printed anatomical model can be generated for one or more of the following purposes:

- *Surgical planning* to facilitate the planning of a given procedure by showing the anatomical details of the surgery site and anticipating technical problems; to select the most suitable surgical device (e.g., prosthesis, etc.) among those available; and to define the management strategy, including the best access to the anatomical target.
- *Education and training* to facilitate the comprehension of a surgical procedure on the part of residents and junior surgeons.
- *Simulation* thanks to the use of deformable materials that enable dissection, suturing and performance of anastomosis on patient-specific platforms.
- *Anatomical comprehension* for a better understanding of fine anatomical details which may influence the management of the underlying disease (not just for surgery).
- *Patient counseling* to enhance the patient's understanding of the planned intervention and his/her awareness of the expected outcomes and associated risks.
- *Surgical tools* for the development of ad hoc 3D-printed tools for experimental research in surgical techniques and technologies.

In this paper, we present a systematic literature review on the use of 3D printing for abdominal surgery to provide up-to-date information on the current state of the application of this technology. All the advantages linked to the availability of a physical object have been extensively reported in other fields such as orthopedic surgery or maxillofacial surgery, while the diffusion in abdominal surgery is still limited. This is mainly due to the higher complexity in medical image processing of soft abdominal tissues, with respect to bones or vessels with medium contrast injection, making more difficult to create the virtual model to be 3D printed. In this context, an overview of state of art applications in abdominal surgery will possibly boost the spread of 3D printing also in this field.

We will also join the discussion by providing information on our 5-year experience with 3D printing for medical applications at a general hospital.

Materials and methods

Search criteria

Three databases were used for the query: PubMed, Web of Science, and Embase. The search strings were first run on PubMed and then adapted to the other databases, according to the specific formulation constraints of each. A filter for the language was applied, limiting the search to documents in English. No filter on the publication year and no filter on the type of publication were applied, thus including conference proceedings, editorial material, meeting abstracts, technical notes, posters, etc. The query was applied to both the title and the abstract. Search strings were made up of three groups of keywords combined through the AND operator. Keywords of each group define, respectively (i) the technology of interest, i.e. 3D printing, (ii) the aim of its use (planning, preparation, evaluation, training or education) and (iii) the anatomical region of application (the abdominal cavity), also specifying the main structures of interest, i.e. the liver, pancreas, kidney, spleen, and biliary ducts. Keywords coming from the database dictionary (e.g., "Mesh" terms for PubMed and "Emtree" words for Embase) were included when available, along with their corresponding free term, since they involve two different search engines (e.g., "Printing, Three-Dimensional" [Mesh] and "Three-Dimensional Printing"). With respect to the anatomical regions, we also included partial terms (e.g., biliar*, pancrea*) to overcome nomenclatural limitations.

Data analysis criteria

The output of the selected search queries was processed using RefWorks software [2], to eliminate duplicates. Afterwards, papers were analyzed according to the exclusion criteria listed in Table 1. The screening was first run relying only on the publications' title and abstract, then on a full text basis.

The resulting publications were then analyzed to retrieve the information pertaining to the specific use of the 3D printing technology. In particular, data were collected on: the 3D printing category and the specific machine and materials described in the report, the type of application of the 3D printed model (surgical planning, education and training, simulation, anatomical comprehension or patient counseling) and the target anatomical district. The number of clinical cases reported in each publication was also recorded. For the nature of the present work, no Institutional Review Board approval or written consent is required.

Results

Search queries produced a total of 296 records on the three databases (Fig. 1) as of December 19th, 2018. After duplicate removal, 184 papers were analyzed according to the selected exclusion criteria, leading to a final pool of 97 publications.

A pattern of progressive increases in the number of publications on 3D printing for abdominal surgery is clearly visible over the last 10 years (Fig. 2), even if with lower numbers with respect to the diffusion in other surgical specialties. The trend follows a similar spread of 3D printing technology on the global market. The first publication appeared in 2008 [3]. Thirty-five publications are in the form of abstracts, conference proceedings, supplements or posters. Seventeen publications belong to only a few research groups (Sugimoto et al. [4–11], Chandak et al. [12–14], Fang [15–17], and Marconi et al. [18–20]).

Table 1 Exclusion criteria for the medical literature search

Studies on animals	Publications dealing with studies on animals
Review articles	Publications presenting a review of 3D printing applications are source of redundancy
Not about abdominal cavity and its content	Publications not dealing with the anatomical districts of interest
Preparatory studies for 3D printing	Publications dealing with 3D virtual models suitable for 3D printing but not actually carrying out the 3D print as part of the work. No 3D printed models are presented in the paper
Studies on materials only	Publications focused only on the properties of 3D printed materials
Duplicates	Publications presenting the same results but in a different format (e.g. conference proceeding and full paper): we consider only the most extensive format

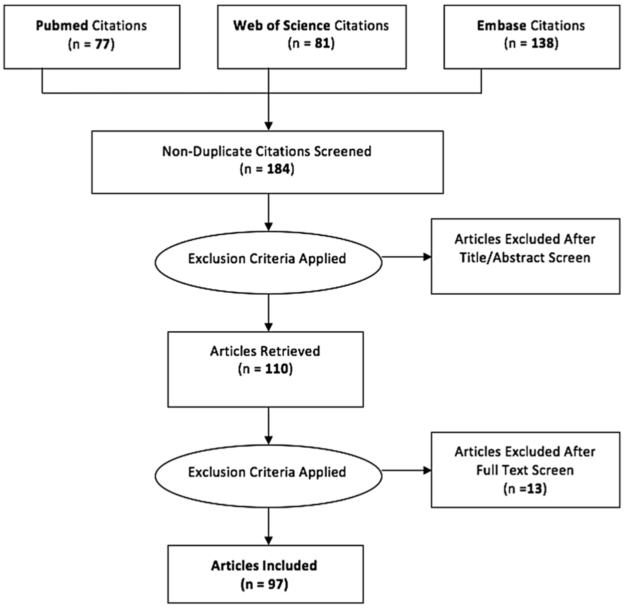


Fig. 1 Flow chart of the publication screening process

Technology

Three-dimensional printing technology can be used either for the direct realization of the final model or for the production of a mold, to cast the desired material. The latter application, also called "indirect 3D printing," combines the advantages of geometrical freedom brought by standard 3D printing with the use of highly deformable materials unsuitable for direct printing or complex to handle (typically silicone, latex or polyurethane). Seventy-nine of the analyzed publications reported a direct 3D printing approach, with only 11 describing an indirect approach [21–31], while in seven papers both approaches were used to generate the final model [3, 32–37].

Thirty-six articles reporting on direct 3D printing described using material jetting technology, considered to be the most reliable in generating anatomical models of abdominal organs, thanks to its accurate control of the mechanical properties [6, 10–14, 18, 19, 29, 34, 35, 38–62]. In only three cases was this technology adopted for indirect printing, through the creation of a mold in which a silicone mixture was poured [29, 34, 35].

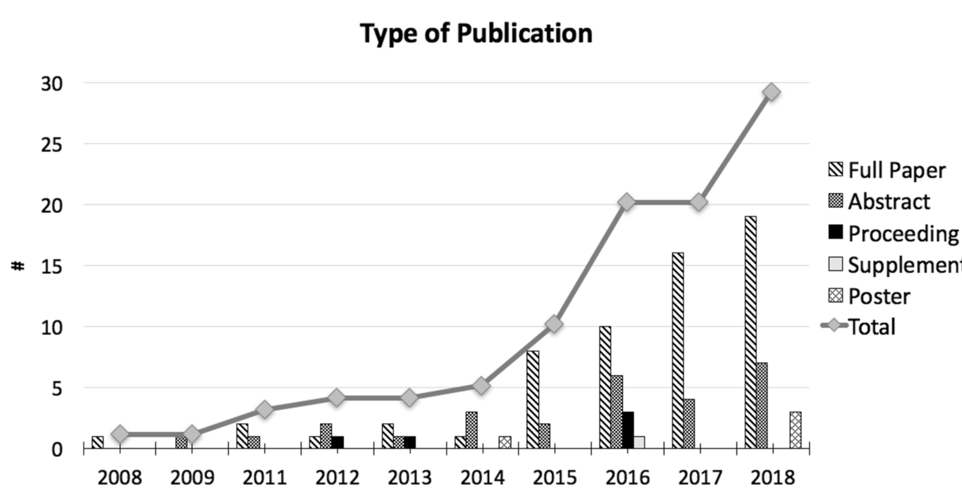
Twenty-two publications reported using material extrusion [22, 23, 25, 27, 30, 31, 33, 37, 49, 63–75]. This technology is characterized by a lower degree of accuracy and resolution and less control over material properties as compared to material jetting. However, the materials employed are much cheaper (e.g., acrylonitrile butadiene styrene or polylactic acid thermoplastic filaments). That is why this technology is the most popular for indirect 3D printing applications, to create the mold which is subsequently destroyed to retrieve the casted model [22, 23, 25, 27, 30, 31, 33, 37].

Ten publications described employing binder jetting technology [3, 20, 24, 32, 35, 76–80], which produces a high-chromatic resolution and is less expensive than material jetting. However, the resulting printed objects are extremely fragile, unsuitable for the production of finer parts, like small blood vessels. On the other hand, this technology is useful for molding applications [35]. Less frequently used technologies are powder bed fusion—with the use of polyamide powders [38, 44, 62, 81, 82]—and vat photopolymerization [83–87], both employed in only five reports. Finally, 28 publications did not mention the 3D printing technology used [3–9, 15–17, 21, 26, 28, 34, 36, 70, 88–99]. This might have to do with the practice of outsourcing 3D printing to external laboratories or private companies.

Anatomical district

The distribution of 3D-printed objects in relation to the anatomical district of interest is summarized in Fig. 3.

Fig. 2 Nature of relevant studies over time



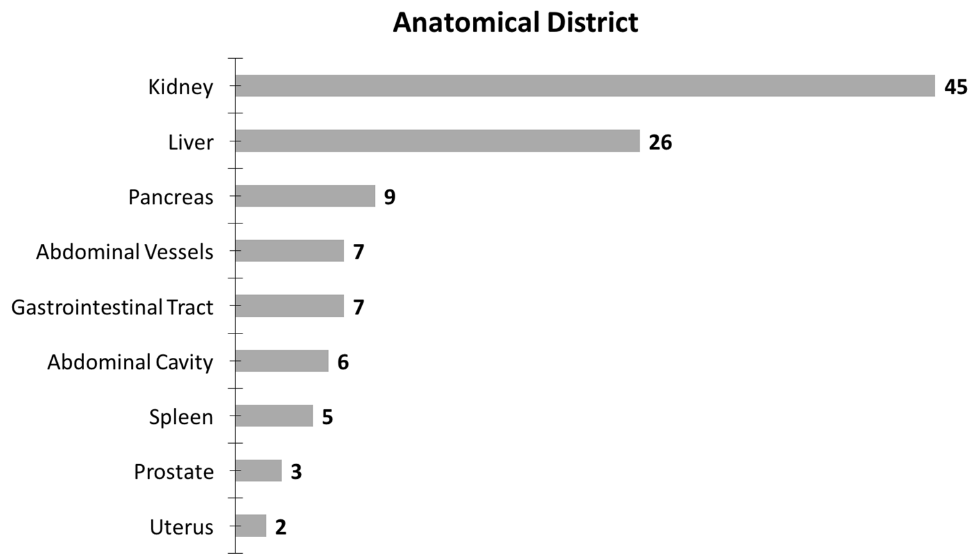


Fig. 3 Frequency of publication in relation to the anatomical site

Kidney

Our analysis showed that the most common 3D-printed anatomical model was of the kidney, with 45 cases. In 21 cases the model was generated in the presence of a kidney mass to assess its resectability [6, 8, 18, 23, 29, 43, 53, 55, 59, 60, 62, 65, 67, 70, 73, 77, 89, 90, 93, 95, 99], which also occurred with four pediatric patients [12–14, 92]. In five cases, the 3D models were used in the planning process for a living donor kidney transplantation [12–14, 18, 96]. These surgical procedures were all performed through a laparoscopic or robotic approach (partial or radical nephrectomy) [28, 36, 38, 73, 74]. In nine cases, the 3D models were generated to evaluate resectability with no mention of the planned surgical technique [4, 26, 37, 48, 50, 69, 83, 88, 98]. In seven cases, the 3D-printed models were used to plan a kidney stone removal, through a percutaneous nephrolithotomy approach [3, 21, 49, 54, 66, 74, 89]. Finally, a 3D-printed kidney was also used as an aid in obtaining the informed consent of patients scheduled for a cryoablation procedure [56].

Liver

Liver models were the subject of 26 reports. A common indication in this setting is the planning of a major hepatectomy [31, 34, 35, 61, 78] or of complex hepatic tumor resection [4, 39, 87, 94, 97]. In two cases the models were used as an additional tool in the assessment of hepatic metastases from colorectal carcinoma following chemotherapeutic treatment [22, 33]. In two reports, the underlying disease was a hepatoblastoma [45], with one case involving pediatric patients [92]. Planning of living donor hepatic transplantation represented an additional indication, both in the adult [46] as well as in the pediatric [91] population. Elsewhere, 3D-printed replicas of the liver generated from healthy patients' medical images [79] as well as from cadaveric scans [80] were used to highlight the normal liver anatomy for educational purposes [81]. Other 3D-printed liver models were employed for training purposes in procedures involving the extrahepatic biliary tree, such as endoscopic maneuvers (flexible choledoscopy [58], laparoscopic choledochal surgery [24] or laparoscopic hepatobiliary surgery [11]). Finally, models were also printed for non-specified hepatic surgery [69], hepatolithiasis [16], complex liver resection [17] and for the production of liver phantoms for the validation of a hepatic vessel segmentation algorithm [85].

Pancreas

Nine publications focused on 3D printing of the pancreas [10, 15, 18, 19, 40, 41, 69, 76, 77], either limited to the reproduction of this gland only, or in combination with a 3D reconstruction of surrounding structures and organs, to plan a pancreatectomy in the setting of a pancreatic tumor.

Spleen

Models of the spleen were produced to plan a splenectomy [18, 20] or to assess the management of a splenic artery aneurysm: either in view of its endovascular treatment or before a laparoscopic or robotic surgery [44, 64]. One case dealt with the reproduction of a large number of abdominal organs, including the spleen, for evaluation of a pediatric malignancy [92].

Abdominal vessels

One report explored the use of 3D-printed models to assess abdominal visceral aneurysms [63]—including splenic, hepatic, gastric, epigastric, gastroduodenal and pancreatico-duodenal aneurysms. Another publication reported the case of a left renal artery aneurysm model [75]. A model of central mesenteric vascular anatomy was also generated for intraoperative navigation during radical D3 right hemicolectomy for cancer (central mesocolic excision) [86]. Furthermore, we found four publications dealing with the 3D printing of models for the planning, simulation or anatomical evaluation of abdominal aorta surgery (due to abdominal aneurysm or occlusive disease) [27, 42, 68, 84]. Six publications were aimed at producing a 3D-printed model of the whole abdominal cavity [5, 9, 25, 32, 73]; due to the preliminary nature of some of these studies, no details were presented on the specific structures addressed, while in two cases the production of a complete phantom for surgical simulation was described [25, 32].

Others

Seven reports dealt with the generation of segments of the gastrointestinal tract, including models of bile ducts [57, 58, 71] and of perianal fistulae [72]. Models were generated for endoscopic submucosal dissection [82], for the planning of percutaneous endoscopic gastrostomy [30] and for the planning of endoscopic submucosal dissection. A model was also created for enhanced visualization of multiple esophageal diverticula [51].

Other publications dealt with the generation of models to simulate robot-assisted radical [38, 62] or partial [8] prostatectomy or for the simulation of a laparoscopic hysterectomy [47] and flexible uteroscopy [52].

Number of clinical cases

Seventy of the analyzed publications presented the use of 3D-printed objects to manage a single clinical case or fewer than ten cases. Only 13 reports described the generation of 3D-printed models for more than ten clinical cases, while 14 publications did not mention the exact number of treated cases.

Type of application

Each report was also labeled with respect to the intended use of the 3D-printed model (Fig. 4), using up to three categories of application for each publication. The most common intended use for 3D-printed models was surgical planning (55 papers), followed by education and training (39 papers) and anatomical comprehension of the area of interest (35 papers).

In 11 cases, the additional recognized value of the model was linked to intraoperative navigation: the surgeon reported the use of these graspable objects to enhance his/her orientation during the procedure. In ten publications, the use of the 3D model was purposely aimed to facilitate explanation to the patient and his/her family of the underlying disease and the planned intervention, with its related technical challenges. Eight reports presented the realization of a complete phantom for surgical simulation: these models included several abdominal structures, typically placed into a reproduction of the abdominal cavity. Particular attention was paid to the material to be used for abdominal organs, to reproduce the haptic characteristics of the tissues as well. Given the

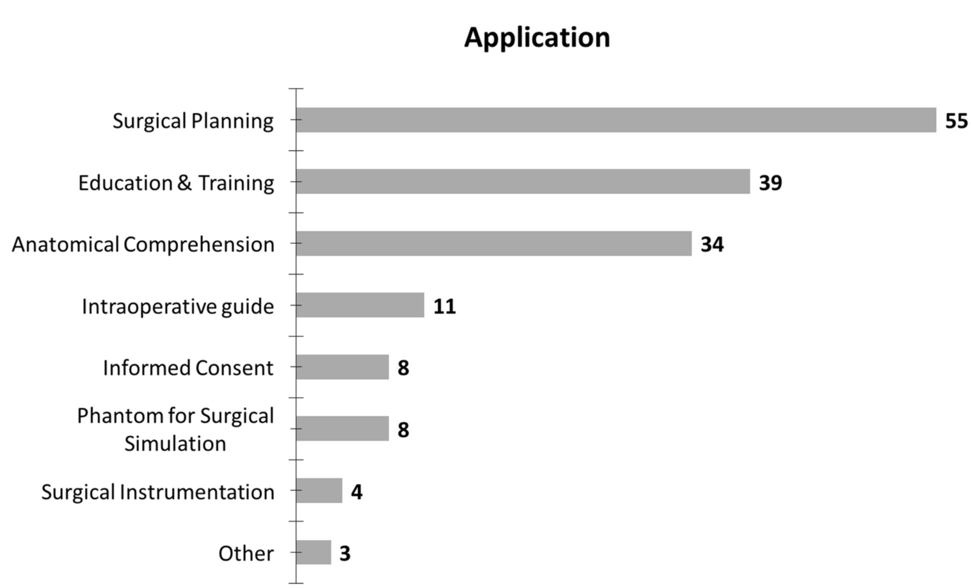


Fig. 4 Division of publications with respect to the intended use of the 3D-printed model

difficulty of obtaining realistic mechanical properties with direct 3D printing technology, the molding technique was usually employed in this setting [24, 25, 27, 32, 37]. Only four papers dealt with the production of surgical instrumentation: a liver retractor for surgical resection and/or ablation [94], an overtube system for endoscopic submucosal dissection, enabling independent use of two manipulators [82], and 3D printed models to be used for the design of fenestrated stent grafts to repair endovascular aneurysms [42, 68]. Finally, three publications dealt with preclinical applications, such as the validation of new segmentation algorithms (for hepatic vessels [85] or for the pancreatic parenchyma [76]) or the comparison between homemade and professional 3D printers for anatomical model production [98].

Discussion

Three-dimensional printing technology is playing an emerging role in medicine, as highlighted by the growing amount of medical literature on this topic. The literature review presented here shows how 3D printing technology has started to spread in the area of abdominal surgery as well. A relevant increase occurred in the number of publications on this subject in the last 10 years, moving from 2–3 publications per year in 2008–2009 to 20–30 papers per year in 2017–2018. Three-dimensional printing technology came into general surgery later with respect to other surgical specialties such as orthopedics or maxillofacial surgery, due to the higher complexity of the image elaboration process, which must be mastered to generate a model suitable for 3D printing. The kidney and liver are the most addressed anatomical districts, possibly thanks to their regular morphology and good visibility on medical images, while the most common application is surgical planning, followed by education, training and anatomical comprehension. The most frequently employed 3D printing technologies are material jetting and material extrusion, although many reports do not provide technical details on the manufacturing process. Seventy-three percent of publications report on fewer than ten clinical cases. The presence of a significant amount of preliminary products of research, such as abstracts and posters, suggests that the adoption of 3D printing technology in this area is not yet a consolidated practice. The potential clinical benefit of 3D-printed anatomical replicas is highlighted in all the reports considered in this review. For surgical planning, the most common intended use of 3D-printed objects, the publications considered in this review unanimously recognize the value of this technology in aiding the surgeon to understand the target anatomy, select the most effective surgical strategy, identify the best access for the laparoscopic approach and anticipate certain intraoperative challenges. Three-dimensional printed models also proved to be useful tools for educational purposes, training and preoperative counseling. Three-dimensional printing has enabled the transition from the virtual world to the physical one: from a technological point of view, the advent of new 3D printers allows the combination of different materials with high resolution for the production of realistic replicas that reflect intraoperative conditions. The high number of reports of renal models is probably due to reasons of technical feasibility: kidneys are clearly visible in medical images (MRI and CT) and, consequently, easier to segment and reconstruct. Moreover, they feature a smooth and regular morphology of parenchyma and vasculature, limiting problems in the production and finishing of 3D-printed models. The combination of 3D visual feedback with the manual exploration of the physical 3D-printed model is able to improve detailed anatomical comprehension and to increase, in accordance, surgical proficiency [20]. In fact, 3D-printed models, as compared with the available alternatives (namely MDCT scan images and 3D digital reconstructions), allow a faster and clearer understanding of a patient's anatomy. Less experienced users such as medical students and residents can perceive the highest benefit, since they lack the experience that is required to build a mental image of the anatomy based on radiological images. Three-dimensional printed models help to transfer complex anatomical information to clinicians, which proves to be useful in preoperative planning, as well as for training and intraoperative navigation. The assessment of anatomical information takes less time when using 3D-printed models than when performed with the corresponding virtual 3D reconstruction or with conventional analysis of 2D slices of MDCT scans [18].

Deformable materials can also be used to reproduce the morphological and mechanical properties of human tissue with greater accuracy, paving the way for more realistic surgical planning, and opening up a new frontier for training on patient-specific platforms. These models are suitable for surgical dissection and the division of vessels and their anastomosis, enabling a realistic simulation of the critical steps of selected procedures and consequently supporting the assessment of operative challenges and of the most suitable technical solution for these. The availability of standardized 3D-printed training models will also facilitate basic research on surgical training, especially in minimally invasive surgery [100]. Preoperative counseling with the patient and his/her family with the support of a 3D model is a valuable opportunity to set realistic expectations regarding the extent of surgery and to discuss possible complications; this can often make the patient more confident when he/she enters the operating room. The availability of a life-size 3D model has positive implications concerning informed consent and other legal issues. Patients' awareness of the proposed intervention results increased markedly when a 3D-printed model was available [101]. A further application which deserves to be mentioned is the potential use of 3D printing technology to the production of patient-specific tools to be used during the intervention. Although we did not find any example coming from the abdominal surgery field, this kind of application is becoming popular in different specialties as ENT-surgery [102].

The Pavia experience: 3D4Med, a clinical laboratory for 3D printing

In addition to the above analysis on the available literature on 3D printing for abdominal surgery, we would like to report briefly on our experience in the exploitation of 3D printing technology at our university hospital. "3D4Med" is the name of the clinical laboratory for 3D printing at the Policlinico San Matteo of Pavia, established through a collaboration between the hospital and the Department of Civil Engineering and Architecture of the University of Pavia. The laboratory—which is located in the main lobby of the hospital, together with an open exhibition of 3D-printed anatomical objects—aims to provide patient-specific 3D-printed anatomical models for a wide range of clinical specialties. In the past 5 years, 3D4Med has generated 3D models in reply to queries from general, ENT-maxillofacial, orthopedic, vascular and cardiac surgeons. To cover the widest range of applications, the laboratory is equipped with a variety of 3D printers, such as PolyJet™, desktop SLA, and binder jetting, and employs three full-time biomedical engineers. The usual requests addressed by the laboratory fall into two main categories: the need for visual inspection only and the need for mechanical interaction (simulation). When the model is intended for visual inspection only, the focus is on creating a high-resolution replica of the anatomy of interest. Several manufacturing solutions permit the creation of this kind of model; the mechanical properties of the printed materials are of secondary importance, with the emphasis placed on chromatic properties and transparencies, to best highlight crucial anatomical information. To enhance the visibility of hidden or less accessible structures, the anatomical model can be made of artificially produced interlocking parts. This technique allows the user to open the model and assess its internal anatomy, which may not always be clearly visible from the external surface even when a transparent material is used. Indeed, the use of transparent material will invariably produce some degree of optical deformation of the model's interior, altering the user's visual perception. When a model is instead generated for simulation purposes, we utilize materials that can mimic the biomechanical features of the tissues or organs involved. Given that we are dealing with soft tissues and organs, deformable materials are mandatory. In this context, having the ability to combine multiple materials within the same product improves the quality of the simulation by reproducing the different mechanical behavior of different tissues. Such models are suitable for the simulation of certain key steps of open, laparoscopic and robotic intervention for the general surgeon (e.g., vessel clamping, cutting and suturing) (Figs. 5, 6).

The fixed costs of establishing our 3D printing laboratory were in the range of 500,000 euros (including the space, air-intake controls, office equipment, computers,

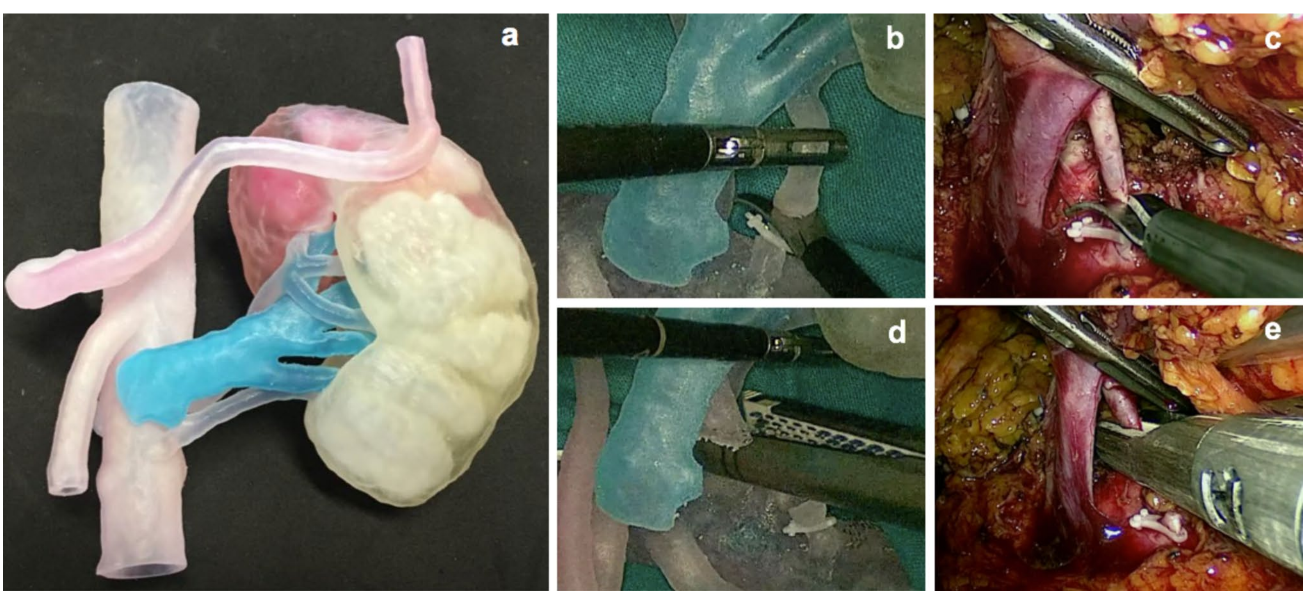


Fig. 5 Model of a living donor's left kidney to simulate a robotic nephrectomy (**A**) and arterial control performed on the model and on the patient, namely cutting an inferior polar artery after its clipping (**B**, **C**) and stapling the main renal artery (**D**, **E**)

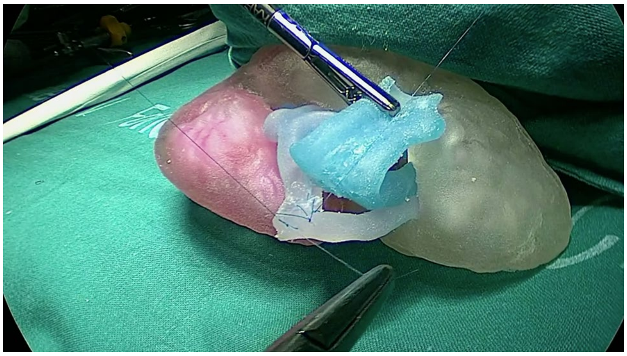


Fig. 6 Model of a living donor's left kidney in which the two renal arteries are joined with a side-to-side suture on the model

energy consumption and three industrial printers). The cost of the material used to produce a single model ranges from 100 to 700 euros, depending on the type of material and the quantity that has to be used. In addition, the generation of the virtual 3D model that is sent to the printer entails an average of 5 h of computer work by a specifically trained technician. The printing time needed to produce each model is between 9 and 22 h, but no human involvement is required for this phase; usually the printer runs overnight. Some post-printing refining is generally needed to remove the support material and glitter the external surface of the model (an hour of manual work). It is therefore difficult to say how much a 3D-printed model costs, since that depends on its quality and on the whole output of the laboratory, which will dilute the fixed costs. To keep these costs sustainable, our advice is to include 3D printing as part of a hospital's range of services, rather than embarking upon specialty-oriented production.

Conclusions

Our review showed the growing role of 3D printing technology in the field of abdominal surgery. According to our experience and to the reports available in the literature, we can draw the following conclusions on the various applications.

Surgical planning and anatomical comprehension

This is the leading field of application of 3D printing in medicine, regardless to the surgical specialty. According to our experience, the higher the anatomical complexity and/or the lower the experience of the surgeon, the higher the benefit brought by the use of a 3D-printed replica.

Education, training and simulation

A good cost-effective practice—especially in university hospitals—could be to collect the most representative 3D-printed models produced for surgical planning purposes to show them to medical students during the teaching activity. This would dramatically improve the comprehension of the specific pathology and the surgical procedure. As for the surgical training, abdominal surgery must face the still limited performance of deformable materials, but the production of patient-specific models to test in advance the intervention would be probably one of the leading research areas of the forthcoming years.

Patient counseling

Commonly, lawsuits for malpractice against the hospital are originated from a poor understanding of operative risks and complications. In our experience, the use of a 3D-printed model to explain the surgical intervention to the patient and his/her relatives increase their comprehension of the technical aspects of the intervention. In case of limited availability of 3D printing facilities, patient-specific models reconstructed from standard anatomies could be employed instead of patient-specific ones.

In conclusion, we believe that 3D printing technology has the potential to permanently join the armamentarium of the general surgeon as a useful tool for management, planning, research and education purposes as well as an effective support for dialogue with our patients and their families. A lot still needs to be done to achieve this goal, especially on the quantification of the actual impact of the technology on the clinical practice. This should be the next research goal on the topic of 3D printing application to the medical field.

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Compliance with ethical standards

Disclosures Andrea Pietrabissa, Stefania Marconi, Erika Negrello, Valeria Mauri, Andrea Peri, Luigi Pugliese, Enrico Maria Marone e Ferdinando Auricchio have no conflicts of interest or financial ties to disclose.

Appendix

Pubmed

((((((((“Printing, Three-Dimensional”[Mesh] OR “Three-Dimensional Printing”[tiab] OR “Three Dimensional Printing”[tiab] OR “3D Printing”[tiab] OR “3DP”[tiab] OR "rapid prototyping"[tiab])
AND
(“planning"[tiab] OR “preparation"[tiab] OR "evaluation"[tiab] OR "training"[tiab] OR "education"[tiab]))
AND
(“liver/surgery”[Mesh] OR “pancreas/surgery”[Mesh] OR “Kidney/surgery”[Mesh] OR “spleen/surgery”[Mesh] OR "abdominal surgery"[tiab] OR hepatic[tiab] OR gastr*[tiab] OR renal[tiab] OR pancrea*[tiab] OR Biliar*[tiab] OR Hepato-biliar*[tiab] OR spleen[tiab]OR splenic[tiab])
AND
English[lang]))))))))

Embase

('three dimensional printing'/exp OR 'three dimensional printing' OR 'three-dimensional printing':ti,ab OR '3d printing':ti,ab OR '3dp':ti,ab OR 'rapid prototyping'/exp OR 'rapid prototyping' OR 'rapid prototyping':ti,ab)

AND ('planning':ti,ab OR 'preparation':ti,ab OR 'evaluation':ti,ab OR 'training':ti,ab OR 'education':ti,ab)

AND ('abdominal surgery'/exp OR 'abdominal surgery' OR 'pancreas surgery'/exp OR 'pancreas surgery' OR 'kidney surgery'/exp OR 'kidney surgery' OR 'abdominal surgery':ti,ab OR 'hepatic':ti,ab OR 'gastr*':ti,ab OR 'renal':ti,ab OR 'pancrea*':ti,ab OR 'biliar*':ti,ab OR 'hepato-biliar*':ti,ab OR 'spleen':ti,ab OR 'splenic':ti,ab)

AND [english]/lim

ISI WEB of SCIENCE

TS = (“three dimensional printing” OR “three-dimensional printing” OR “3D Printing” OR “3DP” OR “rapid prototyping”)

AND

TS = (“planning" OR “preparation" OR "evaluation" OR "training" OR "education")

AND

TS = (“liver surgery” OR “pancreas surgery" OR “Kidney surgery” OR “spleen surgery” OR "abdominal surgery" OR hepatic OR gastr* OR renal OR pancrea* OR Biliar* OR Hepato-biliar* OR spleen OR splenic)

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