Innovation

Advantages and disadvantages of 3-dimensional printing in surgery: A systematic review

Nicolas Martelli, PharmD, PhD,[a,b] **Carole Serrano, PharmD,**[a] **Hélène van den Brink, PharmD, PhD,**[b] **Judith Pineau, PharmD,**[a] **Patrice Prognon, PharmD, PhD,**[a] **Isabelle Borget, PharmD, PhD,**[b,c] *and* **Salma El Batti, MD,**[d,e] *Paris, Châtenay-Malabry, and Villejuif, France*

Background. *Three-dimensional (3D) printing is becoming increasingly important in medicine and especially in surgery. The aim of the present work was to identify the advantages and disadvantages of 3D printing applied in surgery.*
Methods. *We conducted a systematic review of articles on 3D printing applications in surgery published between 2005 and 2015 and identified using a PubMed and EMBASE search. Studies dealing with bioprinting, dentistry, and limb prosthesis or those not conducted in a hospital setting were excluded.*
Results. *A total of 158 studies met the inclusion criteria. Three-dimensional printing was used to produce anatomic models (n = 113, 71.5%), surgical guides and templates (n = 40, 25.3%), implants (n = 15, 9.5%) and molds (n = 10, 6.3%), and primarily in maxillofacial (n = 79, 50.0%) and orthopedic (n = 39, 24.7%) operations. The main advantages reported were the possibilities for preoperative planning (n = 77, 48.7%), the accuracy of the process used (n = 53, 33.5%), and the time saved in the operating room (n = 52, 32.9%); 34 studies (21.5%) stressed that the accuracy was not satisfactory. The time needed to prepare the object (n = 31, 19.6%) and the additional costs (n = 30, 19.0%) were also seen as important limitations for routine use of 3D printing.*
Conclusion. *The additional cost and the time needed to produce devices by current 3D technology still limit its widespread use in hospitals. The development of guidelines to improve the reporting of experience with 3D printing in surgery is highly desirable. (Surgery 2016;159:1485-500.)*

From the Pharmacy Department,[a] *Georges Pompidou European Hospital, Paris; University Paris-Sud,*[b] *GRADES, Faculty of Pharmacy, Châtenay-Malabry; Department of Health Economics,*[c] *Gustave Roussy Institute, Villejuif; Department of Cardiac and Vascular Surgery,*[d] *Georges Pompidou European Hospital; and URDIA - Unité de Recherche en Développement,*[e] *Imagerie et Anatomie - EA 4465, Université Paris Descartes, Paris, France*

THREE-DIMENSIONAL (3D) PRINTING, also known as additive manufacturing or rapid prototyping, is described frequently as a technical and industrial revolution that might significantly change the way we live. This manufacturing method is based on 3D computer models for the reconstruction of a 3D object by the addition of material layers, such as plaster, metal, plastic, and so on.[1] The concept of 3D printing actually began as "stereolithography" in the early 1980s by Charles W. Hull, who started selling the first 3D printers for commercial applications in 1988.[2] Stereolithography enables the creation of an object, usually by curing a photoreactive resin with a ultraviolet laser in a layer-by-layer fashion. Since then, different 3D printing processes have been developed for many applications; in the field of medicine, the numbers of such applications have increased dramatically since the early 2000s.[3]

In health care, three 3D printing processes—selective laser sintering (SLS), fused deposition modeling, and inkjet printing[1]—have emerged and almost overtaken stereolithography in terms of frequency of use. The first of these, SLS, uses a laser to selectively fuse together particles of powdered material within a powder bed. Lowering of the

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Reprint requests: Nicolas Martelli, PharmD, PhD, Pharmacy Department, Georges Pompidou European Hospital, AP-HP, 20, rue Leblanc, 75015 Paris, France. E-mail: nicolas.martelli@aphp.fr.

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powder bed by 1 layer thickness allows the sequential building of an object layer by layer. The second of these processes, fused deposition modeling, is based on the same principle as classic 2-dimensional printing and deposits small beads of thermoplastic material in layers to eventually build up a 3D object. Finally, inkjet printing also uses a printhead that deposits thermally or mechanically droplets of "material ink" layer by layer to form the object. By virtue of its high resolution, inkjet printing is considered currently the most suitable technique for "bioprinting," which is applied in regenerative medicine to produce tissues and organs.[4] Bioprinting represents a huge step forward in tissue engineering and is likely to enable the repair of anatomic defects and the reconstruction of complex organs in the foreseeable future.[5] In the present review, we focus on nonbiologic printing techniques for which the data are most extensive currently.

Many reviews have reported advantages and disadvantages of 3D printing in medicine.[1,6-13] Among the advantages, 3D printing techniques can be used in indications, such as preoperative planning, implant designing, training, and/or education. Specifically in surgical applications, these techniques have been described to provide a better understanding of complex anatomy/morphology or the possibility to create customized implants or surgical guides. Among the disadvantages identified, the required time and cost of the techniques are seen as the most important limitations. Although techniques of 3D printing are used increasingly in surgery, the advantages and disadvantages of their use remain to be investigated. Indeed, in view of the remarkable development of 3D printing over the last decade, close attention must now be devoted to detailing and ranking this distribution, especially in surgery. Such information would help surgical teams intending to develop 3D printing for in-house manufacturing.

The aim of the present systematic review was to identify the advantages and disadvantages reported over the last 10 years, on the use of 3D printing techniques in surgery. We then analyzed their distribution and discussed their relative occurrence in the literature. We focused on surgery and excluded dental surgery from the search.

MATERIALS AND METHODS

Study selection. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed to perform the systematic review. The PRISMA checklist is available as supporting information (Supplementary Table I). In addition, a study protocol was established to clarify the review questions and eligibility criteria (Supplementary Table II). The systematic search was performed on PubMed and EMBASE to collect clinical studies on 3D printing applications in surgery in a hospital context. The search terms used are presented in the study protocol (Supplementary Table II). Limits were defined on language and publication date; only reports in French or English published between February 2005 and February 2015 were considered. Titles and abstracts were screened independently by 2 reviewers to exclude irrelevant or duplicate abstracts. Exclusion criteria were study reviews, fundamental research studies or those with no hospital application, and those involving bioprinting, dentistry, and limb prosthesis. Then, included articles underwent a full-text review. Exclusion criteria were the same as in the first step. When the full text of the publication was not available online, the article was requested directly from the corresponding author.

Data analysis. A data extraction form was developed in Microsoft Office Excel 2010 to standardize extraction and analysis of data. Collected information included first author and date of publication, country, study design and number of patients, medical field, application (ie, anatomic 3D printed models, surgical guide and templates, etc), printing technique, and material used. After a first reading of every article retrieved, 2 researchers (N.M. and C.S.) drew up a list of categories able to regroup the various advantages and disadvantages identified in the studies (Table I). To prevent problems relating to the variability of terms denoting similar items, the categories and their definition were given in the study protocol. The 2 researchers referred to this protocol and grouped independently and under 1 single category all identified advantages and disadvantages concerning 3D printing applications. Data were reported in a spreadsheet (Microsoft Office Excel 2010).

RESULTS

Study selection. After excluding duplicates, 1,067 studies were identified; 794 were excluded based on the content of their titles and abstracts. The remaining 273 studies were considered in their entirety, after which a further 115 were excluded. Thus, a total of 158 studies met the selection criteria and were suitable for complete analysis (Fig 1). The number of published studies showed a regular increase year by year between

Table I. Definition of the categories identifying advantages and disadvantages of 3D printing in a surgical setting

Category	*Definition*
Accuracy	Ability of 3D printing and image acquisition techniques to reproduce patient anatomy or to design precise shapes
Characteristics of the 3D printing technique	Technical properties of the 3D printing technique: materials available, post-processing manipulations, etc
Costs	Increase or decrease of costs resulting from the use of 3D printing (hardware, software, material…)
Feasibility	Ability to be performed in clinical routine
Indications	Purposes for which 3D printing is helpful or without interest
Intraoperative guidance	Ability to guide the surgeon in the operating room, directly at the surgical site
Library and Replication possibilities	Ability to establish a databank of objects in STL format and to manufacture them when necessary
Multidisciplinary approach	Collaborations between different stakeholders (surgeon, radiologist, engineer, etc)
Patient education	Communication between surgeon and patient to explain the pathology and the surgical procedure
Patient outcome	Aesthetic or functional outcomes of the surgical procedure
Preoperative planning	Processes to plan the surgical procedure: definition of the surgical problem, identification of the technical aspects and simulation of the surgical procedure
Properties of the 3D object obtained	Technical features of the 3D object, such as color, height, mechanical or thermal properties
Revision or reoperation	Ability to plan and perform a surgical revision
Risks and complications	Increase or decrease in the incurred risks for patient and surgeon, and in the surgical complications for the patient
Surgeon's skills and expertise	Necessity for specific surgeon skills or expertise to perform the surgical procedure
Teaching and training	Tool for training medical students and residents
Time—surgical procedure	Increase or decrease of time needed for the surgical procedure
Time—preparation	Increase or decrease of time needed to plan the procedure and manufacture 3D objects

3D, 3-Dimensional; *STL*, standard tessellation language.

2005 and 2011, before slightly decreasing in 2012, reaching a peak in 2013, and decreasing again in 2014 (Fig 2).

Characteristics of included studies. The characteristics of the 158 included studies are presented in details in Supplementary Table III [14-171] The included studies were conducted in 37 different countries, and the 5 most represented countries were China (n = 36, 22.8%), Germany (n = 14, 8.9%), the United States (n = 11, 7.0%), Japan (n = 10, 6.3%), and the United Kingdom (n = 10, 6.3%). The included studies focused primarily on maxillofacial (n = 79, 50.0%) and orthopedic operations (n = 39, 24.7%) and most were case reports (n = 70, 44.3%) and case series (n = 62, 39.2%). Of the 158 included studies, only 1 randomized, controlled trial was found. The study sizes ranged from 0 to 126 patients, and only 30 (19.0%) studies recruited >10 patients.

Of the 158 included studies, 113 (71.5%) reported applications of 3D printing to produce anatomic models. A further 40 (25.3%) reported their use to create surgical guides and templates, notably exclusively for operations of bony structures. These latter devices were designed to help the surgeon intraoperatively to achieve optimal alignment or position of the surgical instruments[55,81,139] or properly harvest and graft bone flaps.[84,98] Fifteen studies (9.5%) reported the production of customized implants and 10 (6.3%), the design of molds which were either facial prostheses,[29,94,133,164] such as the ear or nose, or casts used for the production of silicone or wax prostheses.[26,44,91,113] Finally, 1 case study reported the 3D printing of an intermediate wafer positioned between maxillary and mandibular dentition to guide the correct repositioning of the maxilla.[140] Some studies reported several applications.

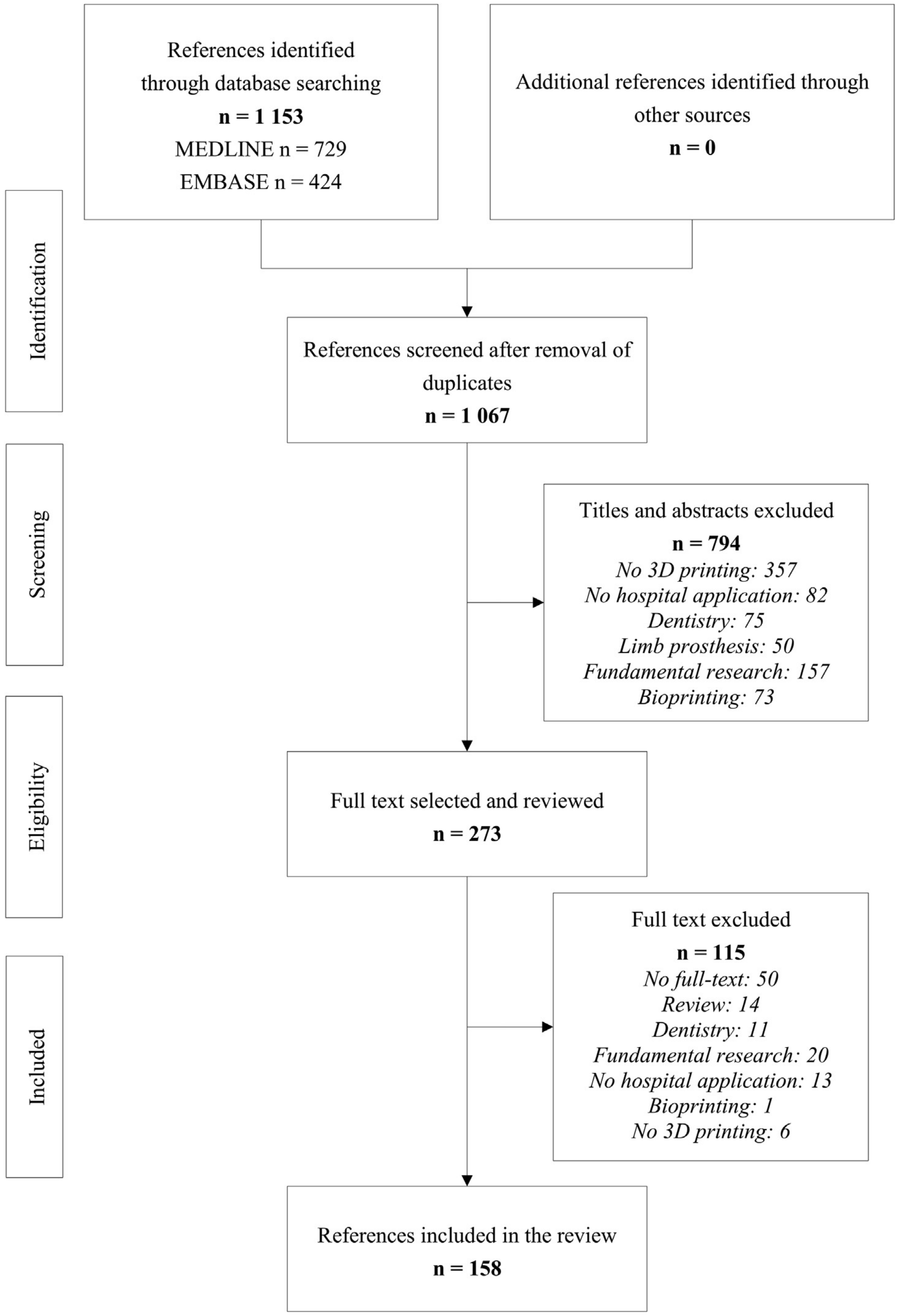

Fig 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow chart of included studies. *3D*, 3-Dimensional.

Concerning techniques used, stereolithography was used in 41 of the included studies (25.9%), SLS in 32 (20.3%), inkjet printing in 28 (17.7%), fused deposition modeling in 22 (13.9%), direct metal laser sintering in 2 (1.3%), and powder depositional modeling in 2 (1.3%). The technique was not stated clearly in 42 studies (26.6%). Some studies reported the use of several techniques. Among these studies, 2 specified only 1 of the techniques used.[90,135] The distribution of materials required according to the 3D-printing technique used is presented in Table II. Of the 158 studies, 24 (15.2%) provided no information on either the material or the technique used.

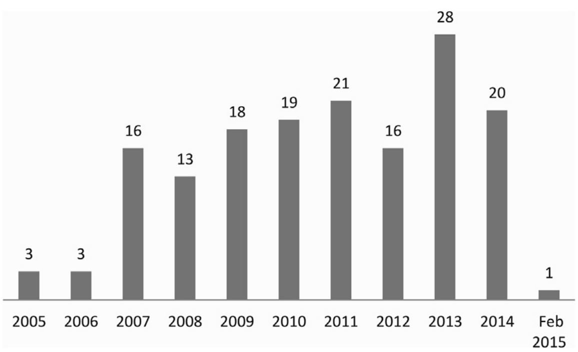

Fig 2. Timeline of studies included.

Data synthesis. Global distribution of advantages and disadvantages is presented in Tables III and IV, respectively. Their distribution according to the technique used and the application reported is presented in details in Supplementary Table IV. Illustrative examples are highlighted below. For more exhaustive references, the reader can refer to Supplementary Table IV. The most reported advantage of 3D printing in the included studies involved the new possibilities for planning the surgical procedure (n = 77, 48.7%). Several surgeons stated that the printed model gave a better impression of the anatomic characteristics[48,66,67,85,112,114] and then facilitated the preoperative planning by visualization of potential difficulties and/or anatomic variations.[17,36,67,79,103,142,144,152,154,159,162] Whatever the 3D printing technique used, many studies underlined that the technique was very helpful for the preoperative planning in complex anatomies.[23,67,68,112,146] This model allowed the surgical team to select the most suitable implants and/or devices for the procedure.[30,45,47,99,100,103,123,159] Surgeons could also anticipate difficulties that may arise by simulating the operative procedure.[27,106,123,124,146,150,152] Many surgeons appreciated the "hands-on" aspect provided by the physical model.[51,66,67,138,145] In addition, 1 study specified that the preoperative simulation with a physical model printed with SLS was easier than that allowed with surgical navigation systems.[90]

The accuracy of 3D printing techniques was seen as a major advantage in many studies (n = 53, 33.5%). Only one of the included studies compared the accuracy of 3 different 3D printing techniques: inkjet, SLS, and a third technique not stated clearly, but possibly the powder bed technique.[135] The inkjet technique was found to present greater accuracy compared with the other two. Elsewhere, whatever technique was used, 3D printing allowed the generation of precise implant shapes that fitted perfectly to the anatomic site[143] or copied exactly the shape of the defect they corrected.[70,75] The consequential lack of implant correction required before its implantation in turn facilitated the surgical procedure and increased its accuracy.[37,49] A similarly increased accuracy of surgical guides and templates obtained with 3D printing techniques improved the precision and positioning of incisions.[31,84] This advantage was highlighted particularly in bony reconstruction with osteotomy.[58,132] The use of an accurate anatomic model also enabled better preforming of implants and to better assess screw trajectories.[76] An excellent level of symmetry achieved in bony reconstruction was also reported.[34,47,170]

Many studies (n = 52, 32.9%) underlined a decrease in operating time by using 3D printing. Thirty-eight studies (24.1%) reported that use of 3D-printed anatomic models improved preoperative planning, thereby contributing to a decrease in operating time. Indeed, the anatomic models enabled preforming implants such as orthopedic plates and also to anticipate the anatomic difficulties.[61,70,73,86,95] In addition, several studies reported that the use of surgical guides and templates (n = 17, 10.8%) permitted a more time-efficient surgical procedure. The use of a 3D-printed surgical guide was also considered a faster approach than use of an image-guided technique.[99,100] Of the 52 studies reporting a decrease in operating time, only a few actually quantified the time saved.[40,67,86,162,168,171] In a comparative study reporting the use of surgical guides in comparison with conventional surgery, the mean time saved was estimated at 5.7 minutes per procedure from a cohort of 22 patients.[168] One case series reported an average saving of 25.2 minutes per procedure with the use of an anatomic model,[86] and a second estimated the time saved to be 63 minutes per case.[67]

Forty-eight studies (30.4%) pointed out the decreased level of risk and number of postoperative complications that resulted from the use of 3D printing. Whatever the application, use of 3D printing technology contributed to improving surgical patient safety by decreasing morbidities.[14,21,40,44,51,61,67,84,89,96,136,155,161] Many studies also reported a decrease in blood loss and transfusion requirements.[37,39,55,163] Also highlighted was a decrease in the radiologic exposure of patients and the surgical team allowed with the use of a surgical guide, which facilitated not only the placement of a device, but also decreases the need for intraoperative radiographic imaging to guide the surgeon.[43,99] In osseous surgeries, the use of

Table II. Distribution of material used according to the 3D printing technique used in the 158 included studies

	3D printing technique used						
Material used	*Direct metal laser sintering, n (%)*	*Fused deposition modeling, n (%)*	*Inkjet printing, n (%)*	*Powder depositional modeling, n (%)*	*Selective laser sintering, n (%)*	*Stereolithography, n (%)*	*Technique not clearly stated, n (%)*
Acrylonitrile butadiene styrene	2 (1.3)	13 (8.2)					1 (0.6)
Cobalt chromium molybdenum	1 (0.6)	1 (0.6)					
Hydroxyapatite						2 (1.3)	
Nylon					4 (2.5)		1 (0.6)
Plaster			5 (3.2)	1 (0.6)	2 (1.3)		8 (5.1)
PMMA					1 (0.6)		2 (1.3)
Polyamide					12 (7.6)	3 (1.9)	
Polybutadiene-styrene resin						1 (0.6)	
Polycaprolactone		1 (0.6)					
Polycarbonate		1 (0.6)					
Polylactic acid		2 (1.3)					
Polypropylene–polyester							1 (0.6)
Polystyrene					6 (3.8)		1 (0.6)
Resin (acrylic)			6 (3.8)		2 (1.3)	24 (15.2)	5 (3.2)
Silicone			2 (1.3)				
Starch			1 (0.6)			1 (0.6)	
Titanium	2 (1.3)	2 (1.3)			2 (1.3)		3 (1.9)
Wax							
Material not clearly stated		5 (3.2)	16 (10.1)	1 (0.6)	8 (5.1)	15 (9.5)	24 (15.2)

Material distribution not equaling 100% can be explained by some studies reporting the use of several materials.
PMMA, Polymethylmethacrylate.

anatomic models helped to decrease the risk of soft tissue trauma.[96] The decreased duration of the surgical procedure was found to decrease the time patients were exposed to general anesthesia and to lessen the exposure time of the wound.[34]

Finally, 38 studies (24.1%) found anatomic models or surgical guides to be helpful tools for use during the surgical procedure. Regarding anatomic models, several reports showed that they were used in the operating room as intraoperative references.[21,43,67,79,105,112,114,116,136,155,161,162] Surgeons found them particularly helpful because they could control positioning without looking away from the surgical field.[55] A similar argument was proposed for surgical guides.[33,55,60,80,111,148] Indeed, surgical navigation software seemed to be more likely to distract the surgeon.[55,112] Several studies stressed that the use of 3D printing led to less misplacements and errors during the procedure.[89,143,171]

Regarding the disadvantages, 33 studies (20.9%) stressed that the accuracy of objects obtained with the 3D printing technique was not always satisfactory. Several studies reported that this inaccuracy was owing to the initial resolution of the 3D image.[23,96,146,152,169] Indeed, some artefacts were found to have likely affected the acquisition parameters and resolution of the image, leading to final errors in volume.[138,152] Another study pointed out that building a 3D model of soft tissue was more difficult than building models of bony structures.[116] Indeed, a small variation in the calculation of radiodensity can have significant consequences on the final object. Finally, accuracy was pointed out by some as being an advantage and a disadvantage. For example, some authors stated that although the accuracy of the 3D object obtained was good enough for the procedure, it is important to consider that some anatomic structures maybe too thin for image acquisition and the technique of printing.[112,152]

The time required to plan and produce the 3D object was viewed as a limitation in 31 studies (19.6%). Several studies concluded that the time to plan and produce the 3D-printed device often

Table III. Global distribution of advantages reported in the 158 included studies

	Advantages	
Category	*n (%)*	*Examples*
Preoperative planning	77 (48.7)	Direct visualization of malformations Better anticipation of anatomic difficulties
Accuracy	53 (33.5)	Precise implant shapes Accurate guides and templates No need for correction or manipulation of the model
Time—surgical procedure	52 (32.9)	Decreased operating time Increased time-efficiency of the surgical procedure
Risks and complications	48 (30.4)	Decreased incidence of postoperative complications such as blood loss, infection, etc Decreased radiologic exposure of patients during the surgical procedure
Intraoperative guidance	38 (24.1)	Positioning improvement
Patient outcome	25 (15.2)	Better surgical results Minimal posttreatment discomfort Better aesthetic results
Costs	24 (15.2)	Less cost per patient Less cost per implant/guide/model
Teaching and training	19 (12.0)	Teaching and training tools
Feasibility	16 (10.1)	No equipment required (external manufacturer) Easy to integrate into the workflow
Properties of the object obtained	15 (9.5)	Good mechanical and thermal properties Easy to work with
Time—preparation	14 (8.9)	Faster than conventional techniques for producing implants
Patient education	13 (8.2)	Improved transfer of information to patients Improved communication with patients
Characteristics of the 3D printing technique	10 (6.3)	Alternative to 3D imaging techniques Automated fabrication
Library and Replication possibilities	7 (4.4)	Creation of model library for replication
Indications	5 (3.2)	Many indications
Surgeon skills and expertise	4 (2.5)	Less requirement for a surgeon expertise
Multidisciplinary approach	3 (1.9)	Better coordination with other specialists allowed
Revision or reoperation	2 (1.5)	Ease of access for surgical revision or reoperation

3D, 3-Dimensional.

delayed the procedure and argued that this technique may be unsuitable for use in emergency cases.[28,54,70,143,171] Even when applied on a routine basis, surgeons were required to anticipate well in advance their preoperative planning and printing.[68] Estimations of the time required for both virtual plan design and printing of an anatomic model varied with a range from 10 hours to 2 weeks.[68,77,98,114,124] Some studies only reported the time needed to print the model, which varied from 3 to 7 hours.[69,124] One time-consuming element even for trained operators seemed to be the computer-aided design, which also required considerable involvement of the surgeon during the preoperative planning.[73,98,114,124,143] A study in orthopedic surgery claimed that the time to bend a plate in conventional surgery was considerably shorter than the time needed to prepare a model.[73]

Numerous studies (n = 30, 19.0%) reported the additional costs of 3D printing techniques as a major disadvantage over conventional methods. The costs of the required equipment, such as computer-aided design software, camera, or the 3D printing machine, were often viewed as a barrier to the use of the technique.[31,36,70,73,85,94,113,123,133] Only a few studies, however, actually estimated or discussed the additional costs in different ways: additional cost per implant, additional cost per patient, and so on.[28,67,94,96,101,113,139,153,156] The additional costs per patient varied widely from 150 to 700€ depending on the reported application.[113,139,153] Some authors stressed that this cost was often

Table IV. Global distribution of disadvantages reported in the 158 included studies

	Disadvantages	
Category	*n (%)*	*Examples*
Accuracy	33 (20.9)	Possible deviations between the computer 3D model and the physical object (image resolution)
Time—preparation	31 (19.6)	Additional preoperative planning time Need to anticipate the production in advance
Costs	30 (19.0)	Costs of the equipment (CAD software, 3D printing machine, etc) Additional cost per patient
Properties of the object obtained	19 (12.0)	Poor mechanical properties Low solidity
Risks and complications	11 (7.0)	Irritation reactions with residual material monomers Increased patient radiologic exposure for imaging
Multidisciplinary approach	9 (5.7)	Complex coordination Too many stakeholders in the process
Characteristics of the 3D printing technique	8 (5.1)	Less efficiency of technique used compared with other production technique
Indications	7 (4.4)	Limited indications
Feasibility	6 (3.8)	Supplementary equipment required (internal production)
Patient outcome	5 (3.2)	Lack of data for determining patient outcome
Surgeon's skills and expertise	5 (3.2)	Results depended on the surgeon's skill and talent
Time—surgical procedure	4 (2.5)	Additional operating time
Preoperative planning	2 (1.3)	No improvement to diagnosis
Library and Replication possibilities	1 (0.6)	Low reproducibility of the impression material

3D, 3-Dimensional; *CAD*, computer-aided design; *STL*, standard tessellation language.

borne by the patient, because these costs were not included in the medical coverage offered in their country.[67,98] In view of the high cost of the technique, a very strict screening of patients was required to limit budgetary expenditures.

Finally, many studies (n = 19, 12.0%) stated that the properties of the object obtained were disappointing. We noted that such disappointment often reported for inkjet printing and especially with anatomic models.[15,45,64,112,138,165] The rigidity of the models was reported as a disadvantage, because the models could not reproduce accurately the compliance of natural tissues.[15,138,165] In other studies, the fragility of the models was also underlined.[64,116] Finally, some 3D objects could not be sterilized and thus were not able to be handled by the surgeon during the procedure.[64,112]

DISCUSSION

In the last decade, 3D printing has become an increasingly important technology in surgery. To our knowledge, this is the first systematic review to analyze thoroughly the distribution of advantages and disadvantages of 3D printing in this medical field. First, we noted that 3D printing techniques were often presented in the included studies as a time-saving tool for use in the operating room; however, this alleged advantage was counterbalanced by the time spent to prepare the model, a frequently reported limitation. Thus, it seemed that the printing itself was rarely the part that took the most time, but rather the more time-consuming aspect was the imaging and data processing. A simple drill guide, for example, can take many hours to produce using 3D modeling. Time saved is thus subjective and depends on the perspective used to assess or appreciate the time saved. In monetary terms, for example, 10 minutes saved in an operating room can potentially have the same value as 1 hour of work on the object design or its production.[172] This consideration was addressed accounted for in one of the included studies[86] in which the cost of operating time was estimated as 16€ per minute and the cost of an anatomic 3D model between 200 and 250€. In this hospital, use of the model was estimated to save an average of 25.2 minutes per procedure ie, 403€ in monetary terms; in this case, the time saved was likely to counterbalance the cost of the 3D model. Also to be considered in this calculation are other consequences of decreasing operating time, including a shortened anesthesia time, which would be expected generally to decrease the requirement for analgesics, lessen the risk of infection, and thus possibly even decrease the need for the use of antibiotics. It is very difficult to generalize such calculations across hospitals, however, because many other factors must also be considered, such as the level of urgency, the type of surgical procedure, the number of cases per year, the country, and so on.

The cost of the technique is also a major limitation reported in the included studies, which is not specific to 3D printing techniques; indeed, the issue of cost is very often a source of concern when new and costly technologies are introduced into medical practice.[173] This point, however, is likely to evolve quite rapidly over the coming years with the decreasing cost of 3D printing.

This cost is not the only barrier to the expanded implementation of the technique in hospitals. Indeed, we noted that the organizational impact was an issue for several surgical teams who stressed that the cooperation between many stakeholders was complex and was a hurdle to the use of the technique. Indeed, 3D software requires specific skills that most surgeons do not have. Considering the huge responsibility played by surgeons at the critical stage of preoperative planning[174] to ensure the outcome of their patients, some surgeons may experience a fear of losing control over the decisions that affect their patients. In contrast, perceived benefits of 3D printing to preoperative planning were reported in nearly one-half of the included studies. The improved understanding of patient-specific, 3D anatomy offered by 3D printing was found to allow surgeons to anticipate possible problems that might arise during the operative procedure and thus potentially improve patient outcome. It seems to be important in this continually evolving and highly specialized field that surgeons accept the support of external technicians without fearing loss over their leadership.[175] Changes in this direction could occur rapidly with a substantial improvement in the accessibility of 3D modeling software.[176]

The high accuracy of the object obtained was valued in one-third of the included studies, whatever 3D printing technique was used. We noted that "accuracy" was difficult to estimate objectively in most studies, which led some authors to consider the resultant accuracy of the device both as an advantage and a disadvantage of 3D printing. Because only 1 study provided a direct comparison of different 3D printing techniques, it is difficult to say conclusively whether inkjet printing is, as they found, more accurate than any other techniques for surgical purposes.[135] The high accuracy of inkjet printing was stated elsewhere, making it the preferred technique for bioprinting[3,177]; however, we also observed that many users found the mechanical properties of models obtained with inkjet printing disappointing, because they did not allow easy handling or a correct simulation of the procedure. The quality of the 3D-printed physical model seems to not only depend on the accuracy of the 3D printing technique, but also and sometimes more importantly on the 3D image resolution, the errors of which likely influence the accuracy of the object.[114] The resolution can also be affected by the 3D slicing software during the segmentation step. Another limitation raised was that most techniques do not enable a precise reproduction of both hard and soft tissues. In procedures involving bony structures, the process of 3D printing can lead to loss of information on soft tissue disease or on vital surrounding tissues, such as arteries or nerves, associated with the bony structures.[101] Nevertheless, this issue may be overcome successfully using multimaterial 3D printers or color models to simulate the different tissues.[156] Finally, postprinting steps, such as cleaning, finishing, and sterilization, are essential to provide suitable and flawless 3D-printed physical objects to surgical teams. The sterilization process chosen depends on the material used to build the object; for example, polylactic acid is not resistant to high temperatures and cannot be autoclaved, thus presenting a critical issue for intraoperative purposes. According to the shape and/or size of the printed object, finishing can be indispensable to remove extra material or support material around the object achieved either manually or chemically, depending on the 3D printing technique or the material used.

Surprisingly, of the 158 studies included, few studies reported the use of 3D printing techniques in the fabrication of customized implants. In our view, this observation underlines that fact 3D printing is still in its infancy for this surgical purpose. Indeed, designing and producing implantable devices is much more challenging than designing and producing anatomic models or surgical guides, which are only used before and/or during the surgical procedure. This is particularly true for hospitals deciding to produce customized implants in house, not only in terms of the equipment required but also the technical expertise not necessarily available within their institution. As a result, 3D printing seems to be outsourced frequently to an external company for this application, using often expensive and complex techniques that hospitals may not be able to afford in the current financial environment.[177] As part of our review, we noted for example that an external company manufactured customized titanium meshes using direct metal laser sintering, which is a very costly process.[30,178] In addition, some regulatory considerations in the design and manufacturing of implantable 3D-printed devices remain very challenging for hospitals.[179] Indeed, the quality controls likely to be imposed by the health authorities to ensure safety and sustainability of the 3D printed products will put added pressure on hospitals aiming to manufacture in-house implants that meet the regulatory standards. The Food and Drug Administration is exploring currently ways of developing new standards that would take into account differences between traditional and additive (3D printing) manufacturing, and also the issue of the in-house manufacturing in hospitals.[180] Finally, our findings suggest that to date all 3D-printed implants have been used only in osseous operations. More reports on applications for soft tissue surgeries might have been expected, because custom-made implants in endovascular surgery, for example, tend to provide better functional outcomes than standard implants in patients with complex anatomy.[181] Modeling mechanical constraints with devices such as endovascular stent grafts, however, remains complicated and requires consistently the expertise of biomechanical engineers. The current technical limits of 3D printing could explain the still rare application of this technology in soft tissue operations. This will very likely may change with the development of bioprinting, which will provide additional possibilities for such operations.

We observed a majority of case reports and case series, and only 1 randomized, controlled trial among the included studies, which is not very surprising to date. These studies are important for hypothesis generation and enable the collection of important data on a new subject[182]; however, case reports and case series are not enough to demonstrate the benefits to surgical procedures of using one 3D printing technique in comparison with conventional surgery alone or to that procedure performed using another 3D printing technique. Although it is important to not consider randomized, controlled trials as the only valid source of evidence, the level of evidence could be improved with well-designed and conducted cohort or case-control studies.[183] In addition, we urge authors to expand on the information provided concerning the technique and/or on the material used in all case reports and future case series. The inadequate level of information on the 3D printing technique found in many of the case report and series included in our systematic review was owing probably to most authors being surgeons who are more focused on the results obtained and the surgical procedure than on the technical details of 3D printing. Guidelines to improve the reporting of experience with 3D printing in surgery could be developed that specify compulsory items, such as the technique used, the 3D printer model, the material, the resolution and so on. The resulting standardized reporting would help to increase knowledge on the applications of 3D printing technique in surgery and improve the quality of published studies.

This systematic review has limitations that need mentioning. First, we did not retrieve in full-text all the articles we identified. Although we made every effort to collect the articles and contacted directly the corresponding authors where necessary, some articles are still missing. In addition, we did not include unpublished studies, which may have introduced some bias, although the quality and level of information provided within such studies may be questionable. Our potential overestimation or underestimation of the occurrence of some advantages/disadvantages cannot be excluded. Indeed, the collection of every item was a time-consuming and laborious exercise. Nevertheless, the 2 investigators attempted rigorously to record all available information and used exactly the same method according to a study protocol. Finally, we noted that the number of advantages reported on 3D printing was twice that of reported disadvantages; however, this could be owing to a publication bias with some authors or journal editors being reluctant to publish negative findings.

In conclusion, until recently, only specialized and private manufacturers were able to produce 3D printed medical devices in optimal conditions and at a reasonable cost. This already has changed with the availability of more affordable 3D printers and user-friendly 3D software that allow an increasing number of health facilities to produce 3D objects in house. The sharing between surgical teams of the cost of hardware, software, and material is, in our opinion, the best way to promote the dissemination of this technology within hospitals.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.surg.2015.12.017.

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