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Evaluation of 3D printing costs in surgery: a systematic review

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Assessment

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Abstract

Objectives. The use of three-dimensional (3D) printing in surgery is expanding and there is a focus on comprehensively evaluating the clinical impact of this technology. However, although additional costs are one of the main limitations to its use, little is known about its economic impact. The purpose of this systematic review is to identify the costs associated with its use and highlight the first quantitative data available.
Methods. A systematic literature review was conducted in the PubMed and Embase databases and in the National Health Service Economic Evaluation Database (NHS EED) at the University of York. Studies that reported an assessment of the costs associated with the use of 3D printing for surgical application and published between 2009 and 2019, in English or French, were included.
Results. Nine studies were included in our review. Nine types of costs were identified, the three main ones being printing material costs ($n = 6$), staff costs ($n = 3$), and operating room costs ($n = 3$). The printing cost ranged from less than U.S. dollars (USD) 1 to USD 146 (in USD 2019 values) depending on the criteria used to calculate this cost. Three studies evaluated the potential savings generated by the use of 3D printing technology in surgery, based on operating time reduction.
Conclusion. This literature review highlights the lack of reliable economic data on 3D printing technology. Nevertheless, this review makes it possible to identify expenditures or items that should be considered in order to carry out more robust studies.

Over the past 10 yr, three-dimensional (3D) printing has grown considerably in the fields of medicine and surgery. Using data from patient CT or MRI scans, this technology allows anatomical models and patient-specific instruments (PSIs) or implants to be developed, and thus finds its full place in the personalization of surgery (1). 3D objects based on patient images are designed by computer-aided design/computer-aided manufacturing (CAD/CAM) technologies and the final product is obtained by adding materials layer by layer. This technology is used in all surgical domains, particularly in orthopedic and craniomaxillofacial surgery, to carry out preoperative planning, to provide intraoperative assistance, or to train students (2). The use of 3D printing technology makes it possible either to manage more complex cases that could not be handled by standard medical devices available on the market, or to improve the outcomes of routine interventions.

The wider use of this technology has made it possible to initiate its clinical evaluation. The first results of initial comparative studies have tended to demonstrate a reduction in operating time and an improvement in aesthetic results (3;4). In 2018, a review of the clinical trial databases identified 92 ongoing clinical trials whose first results are expected within the next 2 yr and which should fill the gaps in clinical evaluation (5).

Nevertheless, one of the major limitations cited as a barrier to its expansion is the extra cost associated with its use (6–9). In the case of in-house production within the healthcare facility, these additional costs may come from the purchase of 3D printers, materials, or even the subscription to software required for device design. In the case of production outsourced to a third-party provider, the additional costs may also be linked to the provision of associated services, such as virtual preoperative simulation. These costs may be partially or entirely funded by the institutions and therefore limit the use of this technology. Consequently, decision-makers in hospital settings, and in the context of limited resources, need information on this topic to support their decisions.

Thus, in parallel with the clinical evaluation, economic evaluation of 3D printing is essential to assess the impact of this health technology and is also a valuable tool to support decision-making. We, therefore, carried out a systematic literature review to assess its economic evaluation, identify the costs associated with its use, and highlight the first quantitative data available.

Material and Methods

Study Inclusion

In order to identify the relevant economic data on 3D printing, a systematic literature review was conducted in the PubMed and Embase databases and in the National Health Service Economic Evaluation Database (NHS EED) at the University of York, following the PRISMA recommendations for reporting (10) (Supplementary file 1, PRISMA Checklist). The search strategy was developed using the PubMed database and then applied to other databases (Supplementary file 2, Study Protocol). The keywords used were "3D printing AND costs and surgery," "Cost-Benefit Analysis AND 3D printing," "Economics" AND 3D printing," "Costs AND Cost Analysis [Mesh] AND 3D printing," "Health Care Economics AND Organizations [Mesh] AND Printing, Three-Dimensional"[Mesh]." Initially, titles and abstracts were screened by two independent reviewers (CS and NM) to identify studies that reported an assessment of the costs associated with the use of 3D printing for surgical applications according to the PICOS (Population, Intervention, Comparators, Outcomes, and Study type) framework (11) (Supplementary file 1, Study Protocol). No inclusion limits were set on the printing technology used or on the place of production (hospital, third-party provider). All printed medical devices were considered (anatomical models, surgical guides, or implants) intended for use in any surgical domain. All items with a cost calculation related to 3D printing were included. Only articles published in English and French between 2009 and 2019 were considered. The exclusion criteria were: studies reporting the use of 3D printing in dental surgery or for the production of external prostheses, studies related to fundamental research or without hospital application or not applied in humans, literature reviews and studies presented at conferences. In a second step, the eligible studies were then selected after a full-text reading by CS and NM, and the exclusion criteria were the same as in the first step. In both steps, in cases of discordant screening or selection, the two researchers discussed the discrepancy until a consensus was reached.

For the included studies, organizational data (place of production, professionals involved), technical data (the type of medical device printed, technology, and materials), and economic data (cost or savings items) were collected. When costs were not in U.S. dollars (USD), local currencies were converted to USD using the exchange rate relating to the study period (the period during which the cost data were collected). When the study period was not clearly stated, we used the exchange rate from the article's publication year. The values were then inflated using USD inflation rates to the base year of the analysis (i.e., 2019) (12). Exchange and inflation rates from the World Bank were used as a source. Consequently, to improve data interpretation, all costs presented in this article are expressed in USD 2019 values.

Quality Assessment

In order to assess the quality of articles screened, we used two established checklists to appraise the reporting and methodological quality of studies included. These tools are all qualitative instruments. In cases of discordant classifications, two researchers (CS and NM) discussed discrepancies until a consensus was reached. Firstly, we used the Consolidated Health Economic Evaluation Reporting Standards (CHEERS) checklist, which is a practical tool used to assess the reporting quality of health economics studies (13). This instrument includes twenty-four items addressed in six categories (title and abstract, introduction, methods, results, discussion, and other); we assigned one point if the item was complete, a half-point for the partial answer, and no points if the information was absent. The maximum score reachable with this tool is normally 24. Nevertheless, some items were not applicable, and so the maximum score reachable was calculated for each article. We also evaluated the level of evidence using the fivefold scale of Sackett et al. (14). This rating system allows rapid identification of the potential clinical quality of the study (Supplementary file 3, Quality Assessment).

Results

Study Selection

After excluding duplicates, 473 studies were identified, of which 429 were excluded on the basis of title and abstract. The reasons for exclusion are presented on the PRISMA Flow Chart (Figure 1). Of the remaining forty-four studies, thirty-five were excluded after the full-text analysis. Thus, nine studies met the eligibility criteria and were included in the systematic review. The characteristics of the included studies are summarized in Table 1. The nine studies were published between 2015 and 2019. The printed devices were mainly anatomical models ($n = 6$). The other printed devices were surgical instruments ($n = 2$), a simulator ($n = 1$), and a surgical template ($n = 1$). No studies have evaluated the production costs of an implant. The printing of the devices occurred in-house in six (67 percent) studies.

Quality of the Included Studies

According to the CHEERS checklist, the quality of the studies included was poor (Supplementary file 3, Quality Assessment) (15–23). The number of items and recommendations gained by each study ranged from 1.5 to 9 with an average of 4 (the maximum reachable score was 22 here). According to the fivefold scale of Sackett et al., six studies were classified as level IV, two as level III, and one as level II.

Cost Evaluation

Nine types of costs were identified in these studies (Table 2): costs in printing materials ($n = 6$), staff costs ($n = 3$), operating room costs ($n = 3$), software subscription ($n = 2$), purchase and maintenance of a 3D printer ($n = 2$), purchase of the printed device from an external supplier ($n = 2$), electricity costs ($n = 1$), an ancillary component for the simulator ($n = 1$), and ancillary services such as preoperative simulation ($n = 1$).

The material cost was the most frequently reported cost and varied from less than USD 1 to USD 146 (15;16;18;19;21;22). Of these studies, four involved an anatomical model, two involved surgical instruments, and one involved a simulator. The printing cost does not appear to be higher for an instrument (USD 2.99 according to Rankin et al., with the purchase cost of the printer) than for an anatomical model (up to USD 146 according to Witowski et al., in material costs only).

The second most reported cost in the studies was the staff cost (16;17;20). In the study by Legocki et al. (16), the cost of a model was calculated from material costs and staff costs and was

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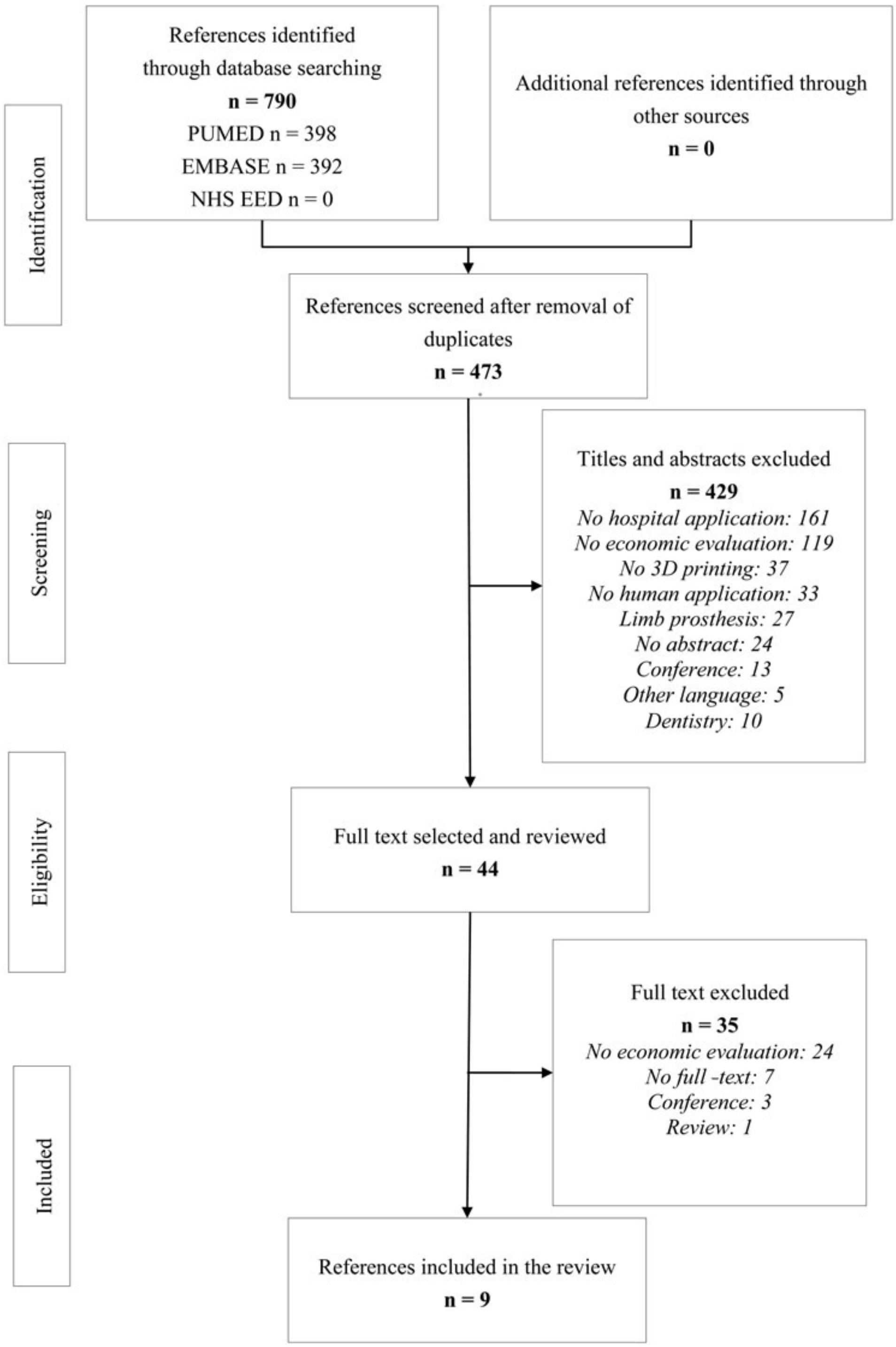

Figure 1. PRISMA flow chart of included studies.

estimated at around USD 97. Resnick et al. (20) focused on staff costs by accurately measuring the time spent on each task and estimated the staff cost at between USD 2,916 and USD 3,114.

The cost of the operating room (OR) was taken into account in three studies (15;17;23). The definition of what this cost included was not clearly stated in the included studies. For King et al. (15), this cost was based on the OR cost/min in their institution (USD 108/min). For Li et al. (17) this cost was USD 4,695/hr and included anesthesia and all related costs. In the Yang study (23), this OR cost was included in the hospital costs without any further detail.

The purchase and maintenance of the 3D printer are mentioned in four studies but taken into account in the cost calculation in only two studies (15–17;19). This cost of printer purchasing varied between USD 2,285 and USD 6,706.

Three studies compared the costs between standard surgery and surgery with a 3D printer (15;17;23). Two studies concluded that the use of 3D printing reduces costs by reducing operating time (15;17).

Three studies also compared the costs of internalized and externalized production (16;17;20). Resnick et al. (20) compared the production of a surgical template by outsourced 3D printing

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Table 1. Characteristics of the Included Studies

First author, date, country	Title	Surgical domain	Application	Provider	Study design	Study objectives	Number of patients	Main results (in USD 2019 values)
King, B.J., 2018, USA (15)	On-site three-dimensional printing and preoperative adaptation decrease operative time for mandibular fracture repair	Maxillofacial surgery	Anatomical models	Hospital	Comparative study (traditional surgery vs surgery planned with 3D-printed models)	Comparing intraoperative time (primary obj.) and operating costs (secondary obj.) between traditional surgery and surgery planned with 3D-printed models	Thirty-eight (nineteen in each arm)	A cost-saving of USD 1,773 (USD 2,457 vs. USD 744) per patient was observed with the use of 3D-printed models
Legocki, A., 2017, USA (16)	Benefits and limitations of entry-level three-dimensional printing of maxillofacial skeletal models	Maxillofacial surgery	Anatomical models	Hospital and third-party provider	Comparative study (in-house models vs commercial models)	Assessing model fidelity, ease of use, costs of production, and clinical indications of in-house models	Three (same patients in both arms)	Cost of an in-house model ranged from USD 98 to USD 99 3D printer purchase (USD 3,127) and annual software subscription (USD 754) not included
Li, S.S., 2018, USA (17)	Computer-aided surgical simulation in head and neck reconstruction: a cost comparison among traditional, in-house, and commercial options	Head and neck surgery	Anatomical models instruments	Hospital and third-party provider	Comparative study (traditional surgery vs in -house models vs commercial models)	Cost analysis comparison among traditional surgery, commercial, and in-house computer-aided surgical simulation (CASS)	-	Traditional surgery was the most expensive (USD 46,953/ case). The average expense was USD 38,885 with in-house CASS and USD 41,673 with commercial CASS
Liu, Y., 2017, China (18)	Fabrication of cerebral aneurysm simulator with a desktop 3D printer	Neurosurgery	Simulator	Hospital	Feasibility study	Developing a cerebral aneurysm simulator at low cost	One	The cost of a simulator was estimated at USD 23.86
Rankin, T., 2015, USA (19)	Three-dimensional printing surgical instruments: are we there yet?	All types of surgery	Instrument	Academic laboratory	Feasibility study	Determining the viability of a 3D-printed retractor	Zero	The cost of an instrument was estimated at USD 2.99, corresponding to one-tenth of the costs of a commercial stainless steel instrument
Resnick, C., 2016, USA (20)	Is there a difference in cost between standard and virtual surgical planning for orthognathic surgery?	Maxillofacial surgery	Surgical template	Hospital and third-party provider	Time-driven activity-based microcosting study	Comparing costs of 3D-printed splints and manual fabricated splints	Forty-three (same patients in both arms)	The virtual surgical planning and 3D printing was statistically less expensive than manual standard planning (3D printing: USD 2,916 to USD 3,114; Manual: USD 3,650 to USD 3,931)
Scerrati A., 2019, Italy (21)	A workflow to generate physical 3D models of cerebral aneurysms applying open-source freeware for CAD modeling and 3D printing	Neurosurgery	Anatomical models	Hospital	Case report	Determining the utility and feasibility issues of in-house production	Five	The mean cost of a model was USD 1.36
Witowski, J., 2017, Poland (22)	Cost-effective, personalized, 3D-printed liver model for preoperative planning before laparoscopic liver hemihepatectomy for colorectal cancer metastases	Liver surgery	Anatomical models	Academic laboratory	Case report	Developing an affordable 3D-printed liver model	One	The cost of a model was estimated to be under USD 150
Yang, M., 2015, China (23)	Application of 3D rapid prototyping technology in posterior corrective surgery for Lenke 1 adolescent idiopathic scoliosis patients	Orthopedic surgery	Anatomical models	Not mentioned	Comparative study (traditional surgery vs. surgery aided by an anatomical model)	Evaluating the effectiveness of 3D rapid-prototyping technology in corrective surgery for scoliosis patients	126 (fifty in 3D group and seventy-six in control group)	Hospital costs were higher for patients treated with 3D-printed models (USD 24,510 vs. USD 23,807)

CAD, computer aided design; 3D, three-dimensional; USD, U.S. dollars.

Table 2. Derivation of Costs (Costs Converted to USD 2019 Values)

	King, B. J. *et al*	Legocki, A. *et al*	Li, S.S. *et al*	Liu, Y. *et al*	Rankin, T. *et al*	Resnick, C. *et al*	Scerrati A. *et al*	Witowski, J. *et al*	Yang, M. *et al*
Fixed costs (USD)									
Purchase and maintenance of a 3D printer	2,285[a]	3,127[a]	6,706 (purchase) 3,053/yr (maintenance)		2,372				
Staff costs		97/model	2,035/case			Surgeon: 8.22/min Assistant: .56/min Receptionist: .41/min			
Operating room costs	108/min		4,695/hr						Not clearly described
Software subscription		754/yr[a]	6,106/yr						
Purchase of the printed device from an external supplier		1,078				2,085			
Ancillary component				3.51					
Ancillary services			4,110/case						
Variable costs (USD)									
Material	<1.07[a]	1.01 to 1.97		20.34	.50		1.36	146	
Electricity				.01					
Total cost per patient/model (USD)	744 in 3D group 2,457 in conventional group	98 to 99	46,953 in control group 41,673 in 3D commercial group 38,885 in 3D in-house group	23.86	2.99	2,916 to 3,114 in 3D group 3,650 to 3,931 in control group	1.36	146	24,510 in 3D group 23,807 in control group

[a]Cost not included in the cost derivation.

with an internalized manual production. Only staff time was taken into account in the cost calculation and the authors found a significant difference in favor of outsourced production. Li et al. (17) determined that there is an economic interest in internalized production when more than twenty-seven cases are performed per year.

Discussion

In the early years of the development of 3D printing technology in the medical field, the additional costs associated with this innovative technology were prohibitive for many users. With the standardization of this technology, a cost assessment has become essential to determine its possible integration into patient care. With this in mind, we were somewhat surprised to find so few studies on this topic and that most were of poor quality.

Of the nine studies, four have as their primary or secondary objective the evaluation of these costs. In other cases, the costs are only additional data, briefly evaluated. This literature review thus highlights a lack of robustness in the methodology of these studies.

In total, in these nine studies, only nine items of expenditure were evaluated. No comparison is possible among these studies because the costs taken into account are too heterogeneous, ranging from the simple cost of the material to the labor costs. If we only consider the material cost, the printing cost of a device is low—less than USD 150 (15–17;19;21;22). The cost differences can be explained by the type of material used and the amount of material required, depending on the complexity of the device to be printed (22). On the other hand, as soon as equipment and staff costs are considered, the cost is much higher and can reach several thousand dollars. It appears that certain items of expenditure, such as the purchase of a printer or a software subscription, are almost never taken into account, even though they can have a significant impact on the cost of a device.

Similarly, modification of logistics may generate additional costs related to the need to deploy or increase specific activities in the healthcare facility, such as sterilization or virtual preoperative planning. Thus, the personal time spent on these new activities must be taken into account in the economic evaluation. This is the purpose of the study conducted by Resnick et al. (20). They measured the time spent at each stage of the production cycle and deducted the costs in terms of staff. In their center, virtual planning with 3D printing was less expensive than the traditional manual method. It, therefore, seems very important to clearly define the production cycle and the people involved to obtain an accurate cost evaluation. However, of the nine studies included, only two cite at least one of the professionals involved, and only one details the role of each of them (18;20;22).

Initially, the purchase of a 3D printer, whose cost could exceed USD 500,000, was not an option for healthcare facilities, which then had to turn to third-party providers. Since these suppliers charge not only for the purchase of a medical device but also for the associated services, the cost of a medical device varies from a few hundred dollars to more than USD 20,000, depending on the complexity of the device to be printed. With the advent of low-cost printers, internalized production has increased and therefore makes it possible to obtain medical devices at a lower cost. In the present literature review, three studies compare the costs of internalized versus outsourced production (16;17;20). Legocki et al. (16) estimated the cost of their model at less than USD 100, while the same device purchased commercially would cost more than USD 2,000. However, this study does not take into account the purchase and maintenance costs of a 3D printer or labor costs. Li et al. (17) show that by taking maintenance costs into account, centers that have little use of 3D printing technology will have a greater incentive to turn to an external supplier.

The studies included in this review focus mainly on the extra costs associated with 3D printing use. Three studies evaluate the potential savings generated by this technology (15;17;20). King et al. (15) estimated a cost savings of USD 1,773 per patient, only based on OR time reduction, but they did not factor in the production cost of the device. According to Li et al. (17), based on a 2-hr reduction in operating time and four cases per year, the use of 3D printing would save USD 4,195 with in-house computer-aided surgical simulation and USD 21,122 with commercial production. Taking into account 3D printer purchase and maintenance costs, the authors estimate that twenty-seven cases per year must be carried out in order to have an economic interest in internalizing production. Ballard et al. (24) also estimated from a literature review the savings achieved through reduced operating time thanks to 3D printing technology and calculated a saving ranging from USD 1,835 to USD 11,094 per surgical case for an anatomical model and from USD 681 to USD 4,115 per surgical case for a PSI. They also estimate that sixty-three models and/or PSIs are the minimum number of cases required per year to have an economic interest in internalizing production.

We identified several reasons that may explain why the evaluated costs vary so much between the included studies. First, although most of the 3D printed devices were anatomical models, they were designed for different purposes in various surgical domains. For example, it is difficult to draw general conclusions from a cost comparison between an anatomical model of a liver and an anatomical model of a jaw. Second, material and staff costs are obviously not the same in the various countries in which the evaluations took place. In addition, we showed that the total costs taken into account ranged from the simple cost of the material to labor costs. This does not allow a direct comparison between studies. Third, we showed that three studies compared internalized and outsourced production of 3D objects; these studies highlighted a significant difference in costs between the two options. These data are rather informative, underlining that the method of production chosen greatly influences the costs. This also explains the variability in the costs observed between studies with differing methods of production.

In light of the present study, there is no economic evidence that clearly shows the cost-effectiveness of 3D printing in surgery. In certain conditions, some studies showed the potential savings that can be made using the technology, but these are very context-dependent models and the generalizability of these results seems limited. Despite the limitations of the studies included, these findings increase the knowledge of the economic impact of 3D printing in surgery. We think that this information is valuable for decision-makers, especially in a hospital setting, because it highlights the sources of the costs of this technology and could help to anticipate and plan the introduction of 3D printing. With ever-growing demands for innovative and costly technologies such as 3D printing, hospital-based health technology assessment seems essential for guiding decisions and helping hospital managers to select the best strategies for their healthcare facility (25). In addition, the present study also underlines the dramatic organizational impacts of such technology. From our point of view, economic evaluations are not sufficient to fully capture the potential impact of 3D printing, and specific organizational evaluations are needed to understand the multidimensional aspects involved in implementing this technology (26).

The present work has some limitations that should be highlighted. First, the small number of studies included in the review does not enable us to draw strong conclusions concerning the economic evaluation of 3D printing in surgery. Second, three different databases were used to perform the systematic review, but it is possible that some studies on this topic may have been published in data sources other than scientific journals. We only focused here on articles published in scientific journals and did not include studies from grey literature, because we expected to collect data of good quality. Third, we used the CHEERS checklist to assess the quality of the articles retrieved, but some of the included studies cannot be considered full economic evaluations. Consequently, the CHEERS checklist may not have been a suitable instrument for checking all the articles included. Nevertheless, we thought that, as a reporting guideline, this checklist was the most appropriate tool that we could use here. Finally, our review was also limited by the relatively poor quality of the articles retrieved.

Conclusion

This literature review highlights the lack of reliable economic data on 3D printing technology. In addition, no studies involving implants were found in the literature, although they are widely used, particularly in maxillofacial surgery. Nevertheless, this review makes it possible to identify expenditures or items that will have to be taken into account in order to carry out more robust studies, such as cost-effectiveness analyses, and to collect information that is useful for decision-makers in a hospital setting. Further economic and organizational studies will be essential to determine the future of this technology in surgery, which is competing with other innovative technologies such as virtual reality (27).

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0266462320000331.

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