



HAL
open science

Benefits of 3D printing applications in jaw reconstruction: A systematic review and meta-analysis

Helene van den Brink, Carole Serrano, Judith Pineau, Patrice Prognon,
Nicolas Martelli

► To cite this version:

Helene van den Brink, Carole Serrano, Judith Pineau, Patrice Prognon, Nicolas Martelli. Benefits of 3D printing applications in jaw reconstruction: A systematic review and meta-analysis. *Journal of Cranio-Maxillofacial Surgery*, 2019, 47 (9), pp.1387-1397. 10.1016/j.jcms.2019.06.008 . hal-03419081

HAL Id: hal-03419081

<https://hal.science/hal-03419081>

Submitted on 20 Jul 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Benefits of 3D printing applications in jaw reconstruction: a systematic review and meta-analysis

Carole Serrano¹; H el ene van den Brink¹; Judith Pineau²; Patrice Prognon²; Nicolas Martelli^{1,2}

¹University Paris-Sud, GRADES, Faculty of Pharmacy, 5 rue Jean-Baptiste Cl ement, 92290, Ch atenay-Malabry, France

²Pharmacy Department, Georges Pompidou European Hospital, AP-HP, 20 rue Leblanc, 75015, Paris, France

Corresponding author: Nicolas Martelli, Pharmacy Department, Georges Pompidou European Hospital, AP-HP, 20 rue Leblanc, 75015, Paris, France. Tel: +33156092575 Fax: +33156093657 E-mail: nicolas.martelli@aphp.fr

Benefits of 3D printing applications in jaw reconstruction: a systematic review and meta-analysis

1 Abstract

Background

Three-dimensional (3D) printing has changed surgical practice over the past few years, especially in maxillofacial surgery. However, little is known about its real clinical impact. The objectives of our study were to identify clinical outcomes that have been evaluated in the literature regarding 3D printing applications in jaw reconstruction, and to quantify the impact of this technology on operating times.

Methods

A systematic review was conducted by searching PubMed and EMBASE to collect comparative studies on 3D printing applications in jaw reconstruction. A meta-analysis of operating times was then performed. A Cochran's Q test was used to determine heterogeneity, and the overall effect size was calculated using a random effects model.

Results

Fourteen studies were included in our review. Eighteen clinical end-points were identified, of which the most frequently reported were operating time ($n = 5$; 35.7%) and the final aesthetic result ($n = 4$; 28.6%). Operating times were significantly lower in the 3D printing groups, with an overall estimated effect of 21.2% (95% CI 10–33%; $p < 0.001$).

Conclusion

The use of 3D printing in jaw reconstruction was associated with a significant reduction in operating times. The end-points evaluated differed largely among the studies. More studies with higher levels of evidence are needed to confirm our results.

Keywords: additive manufacturing, three-dimensional printing, surgery, meta-analysis, systematic review, clinical outcome

2 Introduction

Three-dimensional (3D) printing is a major innovation that has changed surgical practice over the past few years. This technology allows the production of patient-specific anatomical models, surgical guides, and implants, thus introducing personalization to surgical practice (*Rengier et al. 2010*). Using CT or MRI images, prototypes of 3D objects are created by computer-aided design/computer aided manufacturing (CAD/CAM) technologies, and the final product is generated by adding materials layer by layer.

This technology is now well integrated into surgical practice, and almost all surgical subspecialties have embraced its use, including craniomaxillofacial surgery, orthopedic surgery, cardiovascular surgery, neurosurgery, plastic and reconstructive surgery, and liver surgery (*Bartel et al. 2017; Hsieh et al. 2017; Jacobs and Lin 2017; Louvrier et al. 2017; Pucci et al. 2017; Witowski et al. 2017*). Most of the applications reported are for maxillofacial and orthopedic surgeries, including: 3D printing of anatomical models for preoperative planning and simulation, and the pre-bending of osteosynthesis plates; surgical guides for osteotomies, bone harvesting or screw placement; and personalized implants that accurately fit patient anatomy.

In maxillofacial surgery, 3D printing is mainly used in dental implant surgery and mandibular reconstruction (*Louvrier et al. 2017*). It is now a widely recognized surgical tool thanks to its numerous advantages reported in the literature, such as the accuracy of the medical devices produced, the ability to prepare implants prior to the operation, and reduced operating times (*Martelli et al. 2016*). When used in jaw reconstruction, it seems that this technology can improve both aesthetic outcome and functional rehabilitation (*Wilde, et al. 2014*). However, despite a large number of studies in the literature reporting the use of 3D printing in jaw reconstruction, little is known about its real clinical benefits in comparison with conventional

surgical techniques. Most of the data available are from case reports and case series, including only a small number of patients and without comparators.

The objective of our study was to evaluate the clinical impact of using 3D printing techniques in comparison with using conventional surgical techniques in jaw reconstruction. We performed a systematic review of comparative studies to identify the end-points evaluated, and the main outcomes observed.

3 Materials and methods

3.1 Systematic review

A systematic review was performed by searching PubMed and EMBASE to collect comparative studies on 3D printing applications in maxillofacial surgery. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were adopted to report the systematic review. The PRISMA checklist is available as supporting information (S1 Checklist). The search terms used were “three-dimensional printing and patients”, “additive manufacturing and patients”, “computer aided design and prosthesis design and patients” and “rapid prototyping and patients”. Studies were eligible if they included both patients treated with a surgical technique using 3D-printed medical devices (P) and those treated with the conventional surgical technique without using a custom-made device (C) for jaw reconstruction (I), in a hospital setting (S). The 3D printed medical devices could be anatomical models, surgical guides, and/or implants. **All additive manufacturing techniques, such as direct metal laser sintering and fused deposition modelling, were considered in our study.** Only comparative reports in French, English, or Spanish published between 2006 and 2017 were considered. A study protocol (S2 Appendix) was established to summarize eligibility criteria and the search terms used. Titles and abstracts were screened independently by two authors (CS and NM) to exclude irrelevant or duplicate abstracts.

Exclusion criteria were as follows: review articles, studies without a comparison of clinical criteria, studies presented at a conference, fundamental research studies, and those with no application in maxillofacial surgery. Then, a full-text review was performed. Exclusion criteria were the same as in the first step. When the full-text of the publication was not available online, the article was directly requested from the corresponding author.

For eligible articles, data were recorded on a Microsoft Office Excel® 2016 spreadsheet and included: first author and date of publication, study design and number of patients, application (e.g. anatomical 3D printed models, surgical guides, and templates), comparators, the clinical criteria that had been evaluated, and significant outcomes obtained. All primary and secondary endpoints compared in the included studies were extracted for analysis.

3.2 Meta-analysis

A meta-analysis of operating times was performed following the PRISMA guidelines. Mean operating times and standard deviation were collected from prospective studies and were recorded on a Microsoft Office Excel® 2016 spreadsheet. When data were not available in the text, they were directly requested from the corresponding author. A Cochran's Q test was performed to determine heterogeneity, and a random effects model was used to calculate the overall effect size. The significance of the effect size was determined using a standard-normal Z-test. A funnel plot was produced to assess publication bias. For each study, the risk of bias was independently assessed by two reviewers using the Cochrane risk of bias assessment tool (*Higgins et al. 2011*).

4 Results

4.1 Study selection

After excluding duplicates, 2815 studies were identified of which 2741 were excluded based on the content of their titles and abstracts. Subsequently, 74 studies remained in the selection process to be read in full, following which a further 60 were then excluded. Thus, a total of 14 studies met the selection criteria and were suitable for complete analysis (Figure 1).

4.2 Characteristics of the included studies

The characteristics of the 14 included studies are summarized in Table 1. Of the 14 studies, 10 were prospective, of which four were randomized, and four were retrospective. Three-dimensional printing was used to produce surgical guides and templates ($n = 9$), anatomical models ($n = 8$), and implants ($n = 6$). They were mainly produced by laser sintering ($n = 7$) and powder bed inkjet ($n = 3$) techniques. Three studies did not clearly define the additive manufacturing method. The 14 studies included 351 patients (158 in the 3D printing groups and 193 in the control groups). They were mainly mandibular cases ($n = 329$; 93.7%), and the most reported indication was the reconstruction of defects resulting from oncological surgery.

4.3 Comparison of end-points

The end-points evaluated in the literature to demonstrate the benefit of 3D printing in jaw reconstruction were grouped into 17 different items. Table 2 summarizes the end-points evaluated and the outcomes observed. The end-points selected were very heterogeneous; six of them were evaluated in only one study. The most reported end-points were operating time ($n = 5$; 35.7%), final aesthetic result ($n = 4$; 28.6%), and the accuracy of the harvested transplant ($n = 4$; 28.6%).

4.4 Impact of 3D printing applications on operating times

Only two out of five studies comparing operating times demonstrated a reduction in this time with the use of 3D printing technology. This reduction varied greatly among the studies. The largest reduction in operating time (32.7%) was observed in a study that reported the use of patient-specific implants in jaw reconstruction (*Sumida et al. 2015*). Three studies showed that although overall operating times did not differ significantly between the two groups, there was a significant difference in specific surgical times, such as reconstruction time (*Ayoub et al. 2014; de Farias et al. 2014; Sieira Gil et al. 2015; Tarsitano et al. 2016a*), ischemic time, and osteosynthesis time (*Ayoub et al. 2014*). Three out of four studies evaluating reconstruction time defined it as the time taken from the initial shaping of the transplant at the donor site to the final osteosynthesis of the transplant (*Ayoub et al. 2014; Sieira Gil et al. 2015; Tarsitano, et al. 2016a*). The remaining study restricted it to include only the time taken for osteosynthesis and flap molding at the defect site (*de Farias et al. 2014*).

Of the five prospective studies comparing operating times with and without the use of 3D printing, only four reported their mean operating time with standard deviation and only these studies were included in our meta-analysis (Figure 2). These four studies included 106 patients (53 in the 3D printing groups and 53 in the control groups).

The funnel plot highlighted an important publication bias (Figure 3). Only positive results demonstrating a reduction in operating times were published. Table 3 shows the risk of bias assessment for each included study. In all studies, a high risk of bias was noted for performance evaluation and outcome assessment due to the use of non-blinding protocols. Heterogeneity was significant among these studies ($I^2 = 67\%$, $p = 0.03$), so a random effect model was used. The overall estimated effect was 21.2%, demonstrating that the use of 3D printing led to a significant reduction in operating times.

4.5 Impact of 3D printing applications on the final aesthetic result

Four studies evaluated the impact of the 3D printed device by comparing the final aesthetic results, and all found a significant difference between control and experimental groups. The follow-up duration varied from 1 month to 1 year. Three out of the four studies used objective criteria based on image analysis to assess the aesthetic outcome (*Azuma et al. 2014; Jiang et al. 2015; Tarsitano et al. 2016b*). For the remaining study, the analysis was based on subjective evaluation of postoperative photographs by blinded medical and non-medical individuals.

4.6 Impact of 3D printing applications on the accuracy of the harvested transplant

Of the four studies evaluating the accuracy of the harvested transplant, three of them compared the difference between the size of the bone flap removed and the size of the bone flap required (*Modabber et al., 2012a; Modabber et al. 2012b; Ayoub et al. 2014*). Two out of these three studies demonstrated a significant reduction in this difference for the 3D printing group (*Modabber et al. 2012b; Ayoub et al. 2014*).

In the remaining study, this end-point was evaluated by measuring the size of the bone flap taken. The authors showed that this tended to be smaller when 3D printed surgical guides were used (*de Farias et al. 2014*).

4.7 Impact of 3D printing applications on the incidence of complications

Three studies compared complications between control and experimental groups. *Sieira Gil et al.* reported 11 different complications, such as hematoma or infection, and found a statistical difference for only two of them (dental malocclusion and exposure of the titanium plate) (*Sieira Gil et al. 2015*). Blood loss was evaluated in one study by analyzing the number of applied units of erythrocytes and no statistical difference was found (*Ayoub et al. 2014*). This

study also demonstrated that the transplant survival rate was identical between the two groups (90%). The remaining study compared the infection rates (23.1% versus 7.7%) and incidence of mucosal rupture (23.1% versus 7.7%) between the conventional surgery group and the experimental group, respectively, and no statistically significant difference was found ($p = 0.27$) (Sumida et al. 2015).

4.8 Impact of 3D printing applications on the length of hospital stay

Three studies compared the length of hospital stay, which varied from 13.8 days to 17.5 days in the experimental groups and from 16 days to 19 days in the control groups (Ayoub et al. 2014; Sieira Gil et al. 2015; Tarsitano et al. 2016a). One study found that the length of stay was higher in the experimental group than in the control group (Sieira Gil et al. 2015). However, none of the studies found a statistically significant difference.

5 Discussion

To our knowledge this is the first systematic review aiming to evaluate the clinical impact of 3D printing in jaw surgery. In the past decade, many studies have underlined the advantages that 3D printing could bring to surgery, such as the possibility of preoperative planning, which could improve the self-confidence of the surgeon, or the use of specific instruments or implants that accurately fit the patient's anatomy. Nevertheless, these studies were mainly case reports or case series involving fewer than 10 patients (Louvrier et al. 2017). Although low-cost 3D printers are available, additional costs associated with this technology remain a major limiting factor to its widespread use. To analyze cost effectiveness, it is important to objectively determine the impact of 3D printing on clinical outcomes.

Four out of the 14 included studies were prospective and randomized studies. Considering that 3D printing technology has only recently been adopted by surgeons, and in comparison

with results obtained in a previous study we conducted (*Martelli et al. 2016*), this is more than expected. Up until the last few years, the use of 3D printing was limited to complex cases that could not be treated using conventional methods. Consequently, the literature was mainly composed of case reports, and data were abundant for this highly individualized use of 3D printing. Nowadays, 3D printing seems to be more accessible. Surgeons can now apply this technology to a larger number of patients, sometimes in their routine surgical practice. This allows prospective comparative studies to be performed that generate data with higher levels of evidence.

This systematic review shows that a wide range of end-points have been used to evaluate the effectiveness of 3D printing, and the reasons given as to why such end-points were selected are often not clearly explained. The end-points most commonly evaluated in the included studies were operating time and final aesthetic result. This was also observed in a systematic review reporting all the end-points used to evaluate the effectiveness of 3D printing in all surgical domains (*Diment et al. 2017*). It is comprehensible that operating time is often used to evaluate this technology, because it is an objective and easily reportable element with a direct impact on the incidence of complications and costs.

This meta-analysis of jaw reconstruction demonstrates that operating time is significantly reduced when a surgeon uses a 3D printed medical device. This reduction is linked, on the one hand, to a reduction in the time needed to harvest the bone flap (*Modabber et al. 2012b; de Farias et al. 2014*), and on the other hand, to the time needed to reconstruct the defect (*Ayoub et al. 2014; de Farias et al. 2014; Sieira Gil et al. 2015; Tarsitano et al. 2016a*). This is made possible by the opportunity for preoperative planning and the use of patient-specific instrumentation. It is worth noting that 3D printing has only ever been used to guide the osteosynthesis part of the intervention, but never the vascular part. Yet the vascular stage of

the surgery is very complex, and the successful application of 3D printing techniques to this stage would directly impact flap survival and postoperative complications. Few studies have evaluated the duration of the vascular repair stage, so it would be very interesting to measure this in order to appreciate its impact on overall surgical time. This would help to determine how 3D printing applications can better assist maxillofacial surgeons.

The second end-point most evaluated in the included studies was the final aesthetic result, showing a tendency to achieve better aesthetic results with the use of 3D printing technology. In jaw reconstruction it is important to obtain good aesthetic results because this directly impacts on functional rehabilitation, neurosensory disturbance, and thus quality of life. Nevertheless, an objective evaluation of this end-point is difficult, and we noted that in all the included studies little attention was given to patient satisfaction. In addition, patients were followed over a short period, so a long-term follow-up of these patients will be essential to confirm these results.

This systematic review also observed a lack of homogeneity in how techniques have been reported in material and methods sections. Indeed, the 3D printing techniques and materials used are rarely described, although they affect the quality of the 3D-printed device and thus its effectiveness. In the future, it will be necessary to identify which technique offers the best value for money for each type of surgery and application. Also, the end-points evaluated in these studies were very heterogeneous and not always clearly defined. This issue made the comparison of results among studies difficult.

The quality assessment of the included studies in the meta-analysis showed a risk of bias for the outcome evaluation due to the assessor's knowledge of the allocated intervention. This is a recurring issue for the clinical evaluation of medical devices. Blinding outcome assessors may be difficult when the intervention is evaluated during the procedure, such as for the

measurement of operating time. However, blinding could be performed when the effectiveness is evaluated remotely, such as for the aesthetic result for example. In this case, it would be possible to achieve single blinding by the use of independent outcome assessors (*Sedrakyan et al. 2010*). Regarding the publication bias, it is not surprising that only positive results in favor of 3D printing technology were found in the literature. Negative results are often considered as an absence of results by the authors, and journals are more likely to publish positive results (*Bown and Sutton 2010*).

Our study has some limitations that are worth mentioning. First, our systematic review only included articles published in English, French, or Spanish, and a search for non-published data was not conducted. This might also introduce a bias in the results. However, we considered that studies published in English were representative of the overall literature and that non-published data could be less robust than published data, thus introducing a quality bias. Finally, another limitation of our study is that although each full-text article was requested from the corresponding author, some articles could not be collected and were excluded from the complete analysis.

Our work shows that the use of 3D printing for jaw reconstruction is likely to be associated with a reduction in operating times and better aesthetic outcomes. However, to confirm our results, more studies with higher levels of evidence are needed. This will only be possible if guidelines are established for the clinical evaluation of 3D printing in surgery.

6 Acknowledgments

The authors would like to thank Béranger Lueza for his advice and help.

7 Fundings

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

8 Declarations of interest

None

9 Contributors

CS and NM participated in the conception and design of the study, acquisition of data, and analysis and interpretation of data.

CS, HVDB, and NM participated in drafting the article or revising it critically for important intellectual content.

All authors gave their final approval of the version to be submitted.

10 References

- Al-Ahmad, Hazem T., Mohammed W. M Saleh, and Ala'uddin M. Hussein. 2013. Evaluation of an innovative computer-assisted sagittal split ramus osteotomy to reduce neurosensory alterations following orthognathic surgery: a pilot study. *The International Journal of Medical Robotics + Computer Assisted Surgery: MRCAS* 9 (2): 134–41. <https://doi.org/10.1002/rcs.1474>.
- Ayoub, Nassim, Alireza Ghassemi, Majeed Rana, Marcus Gerressen, Dieter Riediger, Frank Hölzle, and Ali Modabber. 2014. Evaluation of computer-assisted mandibular reconstruction with vascularized iliac crest bone graft compared to conventional surgery: a randomized prospective clinical trial.” *Trials* 15: 114. <https://doi.org/10.1186/1745-6215-15-114>.
- Azuma, Masaki, Toru Yanagawa, Naomi Ishibashi-Kanno, Fumihiko Uchida, Takaaki Ito, Kenji Yamagata, Shogo Hasegawa, et al. 2014. Mandibular reconstruction using plates prebent to fit rapid prototyping 3-dimensional printing models ameliorates contour deformity. *Head & Face Medicine* 10: 45. <https://doi.org/10.1186/1746-160X-10-45>.
- Bartel, Thomas, Andrew Rivard, Alejandro Jimenez, Carlos A. Mestres, and Silvana Müller. 2017. Medical three-dimensional printing opens up new opportunities in cardiology and cardiac surgery. *European Heart Journal*, February. <https://doi.org/10.1093/eurheartj/ehx016>.
- Bown, M. J., and A. J. Sutton. 2010. Quality control in systematic reviews and meta-analyses. *European Journal of Vascular and Endovascular Surgery* 40 (5): 669–77. <https://doi.org/10.1016/j.ejvs.2010.07.011>.
- Ciocca, Leonardo, Claudio Marchetti, Simona Mazzoni, Paolo Baldissara, Maria Rosaria Antonella Gatto, Riccardo Cipriani, Roberto Scotti, and Achille Tarsitano. 2015. Accuracy of fibular sectioning and insertion into a rapid-prototyped bone plate, for mandibular reconstruction using CAD-CAM technology. *Journal of Cranio-Maxillo-Facial Surgery* 43 (1): 28–33. <https://doi.org/10.1016/j.jcms.2014.10.005>.
- Diment, Laura E., Mark S. Thompson, and Jeroen Hm Bergmann. 2017. Three-dimensional printed upper-limb prostheses lack randomised controlled trials: a systematic review. *Prosthetics and Orthotics International*, June, 309364617704803. <https://doi.org/10.1177/0309364617704803>.
- Farias, Terence Pires de, Fernando Luiz Dias, Mário Sérgio Galvão, Edson Boasquevisque, Ana Carolina Pastl, and Bruno Albuquerque Sousa. 2014. Use of prototyping in preoperative planning for patients with head and neck tumors. *Head & Neck* 36 (12): 1773–82. <https://doi.org/10.1002/hed.23540>.
- Higgins, Julian P. T., Douglas G. Altman, Peter C. Gøtzsche, Peter Jüni, David Moher, Andrew D. Oxman, Jelena Savović, Kenneth F. Schulz, Laura Weeks, and Jonathan A. C. Sterne. 2011. The Cochrane Collaboration’s tool for assessing risk of bias in randomised trials. *BMJ* 343 (October): d5928. <https://doi.org/10.1136/bmj.d5928>.
- Hsieh, Tsung-Yen, Raj Dedhia, Brian Cervenka, and Travis T. Tollefson. 2017. 3D printing: current use in facial plastic and reconstructive surgery. *Current Opinion in Otolaryngology & Head and Neck Surgery* 25 (4): 291–99. <https://doi.org/10.1097/MOO.0000000000000373>.

- Jacobs C.A., and Lin A.Y. 2017. A new classification of three-dimensional printing technologies: systematic review of three-dimensional printing for patient-specific craniomaxillofacial surgery. *Plastic and Reconstructive Surgery* 139 (5): 1211–20. <https://doi.org/10.1097/PRS.0000000000003232>.
- Jiang, Fei-Fei, Yan Hou, Li Lu, Xiao-Xu Ding, Wei Li, and Ai-Hui Yan. 2015. Functional evaluation of a CAD/CAM prosthesis for immediate defect repair after total maxillectomy: a case series of 18 patients with maxillary sinus cancer. *Journal of Esthetic and Restorative Dentistry*: 27 Suppl 1 (April): S80–89. <https://doi.org/10.1111/jerd.12117>.
- Louvrier, A., P. Marty, A. Barrabe, E. Euvrard, B. Chatelain, E. Weber, and C. Meyer. 2017. How useful is 3D printing in maxillofacial surgery? *Journal of Stomatology, Oral and Maxillofacial Surgery* 118 (4): 206–12. <https://doi.org/10.1016/j.jormas.2017.07.002>.
- Martelli, Nicolas, Carole Serrano, Hélène van den Brink, Judith Pineau, Patrice Prognon, Isabelle Borget, and Salma El Batti. 2016. Advantages and disadvantages of 3-dimensional printing in surgery: a systematic review. *Surgery*, January. <https://doi.org/10.1016/j.surg.2015.12.017>.
- Mazzoni, Simona, Claudio Marchetti, Rossella Sgarzani, Riccardo Cipriani, Roberto Scotti, and Leonardo Ciocca. 2013. Prosthetically guided maxillofacial surgery: evaluation of the accuracy of a surgical guide and custom-made bone plate in oncology patients after mandibular reconstruction. *Plastic and Reconstructive Surgery* 131 (6): 1376–85. <https://doi.org/10.1097/PRS.0b013e31828bd6b0>.
- Modabber, Ali, Marcus Gerressen, Maria Barbara Stiller, Nelson Noroozi, Alexander Füglein, Frank Hölzle, Dieter Riediger, and Alireza Ghassemi. 2012. Computer-assisted mandibular reconstruction with vascularized iliac crest bone graft. *Aesthetic Plastic Surgery* 36 (3): 653–59. <https://doi.org/10.1007/s00266-012-9877-2>.
- Modabber, Ali, Christina Legros, Majeed Rana, Marcus Gerressen, Dieter Riediger, and Alireza Ghassemi. 2012. Evaluation of computer-assisted jaw reconstruction with free vascularized fibular flap compared to conventional surgery: a clinical pilot study. *The International Journal of Medical Robotics + Computer Assisted Surgery: MRCAS* 8 (2): 215–20. <https://doi.org/10.1002/rcs.456>.
- Pucci, Josephine U., Brandon R. Christophe, Jonathan A. Sisti, and Edward S. Connolly. 2017. Three-dimensional printing: technologies, applications, and limitations in neurosurgery. *Biotechnology Advances* 35 (5): 521–29. <https://doi.org/10.1016/j.biotechadv.2017.05.007>.
- Rengier, F., A. Mehndiratta, H. von Tengg-Kobligk, C. M. Zechmann, R. Unterhinninghofen, H.-U. Kauczor, and F. L. Giesel. 2010. 3D printing based on imaging data: review of medical applications. *International Journal of Computer Assisted Radiology and Surgery* 5 (4): 335–41. <https://doi.org/10.1007/s11548-010-0476-x>.
- Sedrakyan, Art, Danica Marinac-Dabic, Sharon-Lise T. Normand, Alvin Mushlin, and Tom Gross. 2010. A framework for evidence evaluation and methodological issues in implantable device studies. *Medical Care* 48 (6 Suppl): S121–128. <https://doi.org/10.1097/MLR.0b013e3181d991c4>.
- Sieira Gil, R., A. Marí Roig, C. Arranz Obispo, A. Morla, C. Martí Pagès, and J. Llopis Perez. 2015. Surgical planning and microvascular reconstruction of the mandible with a fibular flap using computer-aided design, rapid prototype modelling, and precontoured

- titanium reconstruction plates: a prospective study. *The British Journal of Oral & Maxillofacial Surgery* 53 (1): 49–53. <https://doi.org/10.1016/j.bjoms.2014.09.015>.
- Sumida, Tomoki, Naruto Otawa, Y. U. Kamata, Satoshi Kamakura, Tomiharu Mtsushita, Hisashi Kitagaki, Shigeo Mori, et al. 2015. Custom-made titanium devices as membranes for bone augmentation in implant treatment: clinical application and the comparison with conventional titanium mesh. *Journal of Cranio-Maxillo-Facial Surgery* 43 (10): 2183–88. <https://doi.org/10.1016/j.jcms.2015.10.020>.
- Tarsitano, Achille, Salvatore Battaglia, Salvatore Crimi, Leonardo Ciocca, Roberto Scotti, and Claudio Marchetti. 2016. Is a computer-assisted design and computer-assisted manufacturing method for mandibular reconstruction economically viable? *Journal of Cranio-Maxillo-Facial Surgery* 44 (7): 795–99. <https://doi.org/10.1016/j.jcms.2016.04.003>.
- Tarsitano, Achille, Leonardo Ciocca, Roberto Scotti, and Claudio Marchetti. 2016. Morphological results of customized microvascular mandibular reconstruction: a comparative study. *Journal of Cranio-Maxillo-Facial Surgery* 44 (6): 697–702. <https://doi.org/10.1016/j.jcms.2016.03.007>.
- Wilde, Frank, Carl-Peter Cornelius, and Alexander Schramm. 2014. Computer-assisted mandibular reconstruction using a patient-specific reconstruction plate fabricated with computer-aided design and manufacturing techniques. *Craniomaxillofacial Trauma & Reconstruction* 7 (2): 158–66. <https://doi.org/10.1055/s-0034-1371356>.
- Witowski, Jan Sylwester, Jasmine Coles-Black, Tomasz Zbigniew Zuzak, Michał Pędziwiatr, Jason Chuen, Piotr Major, and Andrzej Budzyński. 2017. 3D printing in liver surgery: a systematic review. *Telemedicine Journal and E-Health* 23 (12): 943–47. <https://doi.org/10.1089/tmj.2017.0049>.
- Zhang, ShanYong, XiuMing Liu, YuanJin Xu, Chi Yang, Gerhard Undt, MinJie Chen, Majid S. Haddad, and Bai Yun. 2011. Application of rapid prototyping for temporomandibular joint reconstruction. *Journal of Oral and Maxillofacial Surgery* 69 (2): 432–38. <https://doi.org/10.1016/j.joms.2010.05.081>.

11 Captions to tables

Table 1: Characteristics of the included studies

Table 2: End-points evaluated in the included studies and the outcomes observed

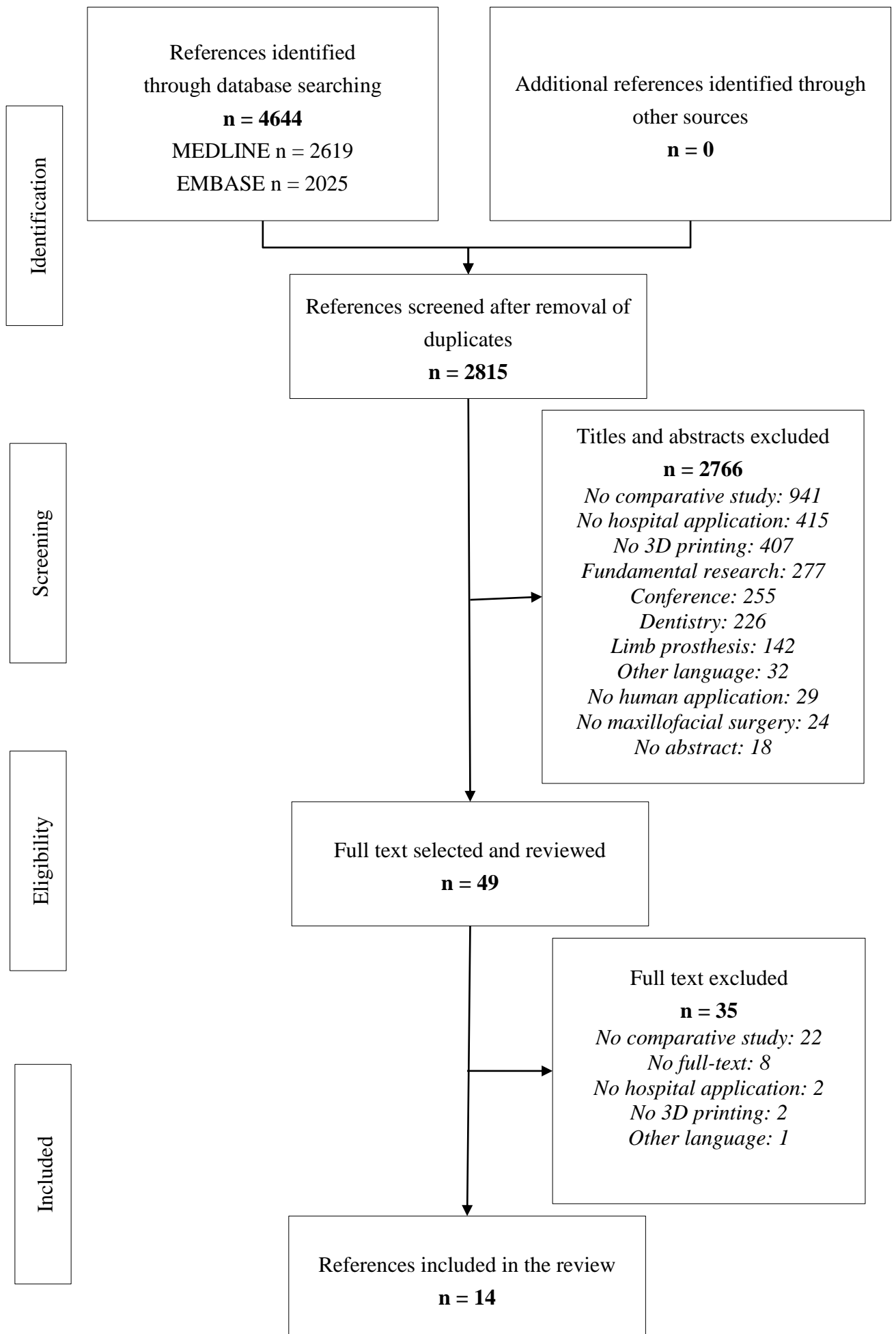
Table 3: Risk of bias assessment (Cochrane risk of bias assessment tool)

12 Captions to illustrations

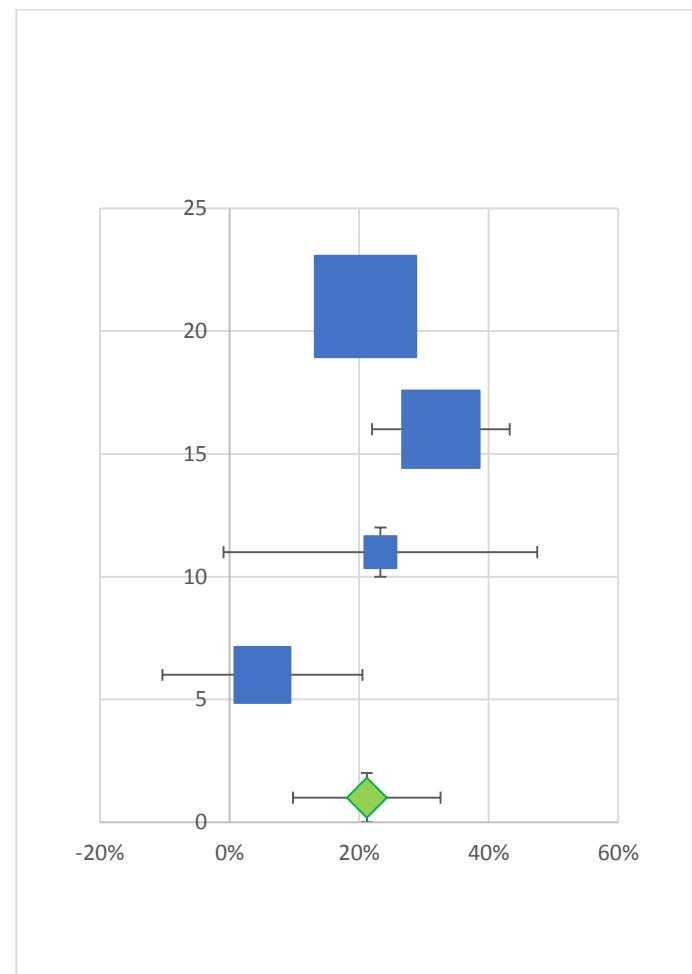
Figure 1: PRISMA diagram

Figure 2: Mean operating times for control group versus 3D printing group: $Q = 9.0$; $DoF = 3$; $I^2 = 67\%$; $p = 0.03$; $Z = 0.54$

Figure 3: Funnel plot evaluating the publication bias



Author	Control group		3D printing group		Weight	Random effect model	
	Operating time (mins)	N° of patients	Operating time (mins)	N° of patients		Reduction in operating time	Confidence Interval (95%)
AYOUB <i>et al.</i> ¹¹	525.2 ± 100.9	10	498.5 ± 83.4	10	21%	5.1%	-10.3% - 20.5%
SIEIRA <i>et al.</i> ¹²	176 ± 58.0	10	135 ± 37.0	10	12%	23.3%	-0.9% - 47.5%
SUMIDA <i>et al.</i> ¹⁰	111.9 ± 18.5	13	75.38 ± 11.6	13	29%	32.6%	22.0% - 43.2%
TARSITANO <i>et al.</i> ¹³	550.5 ± 54	20	435 ± 27.0	20	38%	21.0%	16.2% - 25.8%
		53		53	100%	21.2%	10.0% - 33.0%



$Q = 9.0$; $DoF: 3$; $I^2 = 67\%$; $p = 0.03$; $Z = 0.54$

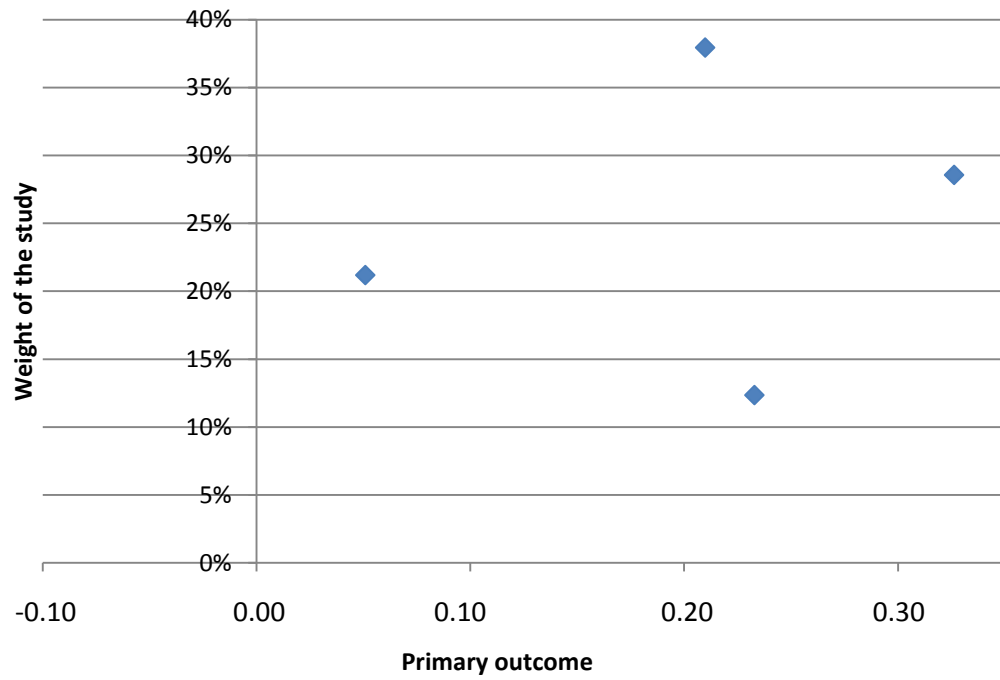


Table 1: Characteristics of the included studies

First author, date, Country	Title	Applications	Study design	N° of patients in 3D group (mandibular/ maxillary cases)	N° of patients in control group (mandibular /maxillary cases)	End-points	Outcomes
Al-Ahmad, 2013 , Jordan	Evaluation of an innovative computer-assisted sagittal split ramus osteotomy to reduce neurosensory alterations following orthognathic surgery: a pilot study	Surgical guides and templates	Randomized prospective study	8 (8/0)	8 (8/0)	Neurosensory disturbance	On the computer-assisted SSRO (sagittal split ramus osteotomy) sides, patients had lower postoperative abnormal thresholds for the Semmes–Weinstein monofilaments on lower lip and chin ($p < 0.05$ at 3 months) and for the two-point discrimination on lower lip ($p < 0.05$ at 1 week) and chin ($p < 0.05$ at 6 months), with fewer abnormal self-reported changes in lower lip sensation ($p < 0.05$ at 1 week) after surgery.
Ayoub et al. 2014, Germany	Evaluation of computer-assisted mandibular reconstruction with vascularized iliac crest bone graft compared to conventional surgery: a randomized prospective clinical trial	Anatomical 3D printed models; surgical guides and templates	Randomized prospective study	10 (10/0)	10 (10/0)	Accuracy of the harvested transplant	In the computer-assisted group, the amount of bone harvested equalled the defect size, whereas the transplant size in the conventional group exceeded the defect site by 16.8 ± 5.6 mm ($p < 0.001$) on average.
						Complications	No statistical difference in blood loss ($p = 0.791$).
						Intercondylar distance	The intercondylar distance was measured before and after surgery; it was less affected in the computer-assisted group compared with the conventional group ($p < 0.001$).
						Ischemic time	Computer-assisted surgery shortened ischemic time in transplant patients (96.1 ± 15.8 versus 122.9 ± 20.4 minutes; $p < 0.005$).
						Length of hospital stay	No statistical difference between the two groups (17.5 ± 7.4 in 3D group; 19.1 ± 9.7 in control group; $p = 0.683$).

First author, date, Country	Title	Applications	Study design	N° of patients in 3D group (mandibular/ maxillary cases)	N° of patients in control group (mandibular/ maxillary cases)	End-points	Outcomes
						Length of ICU stay	No statistical difference between the two groups (2.0 ± 0.9 in 3D group; 2.1 ± 2.1 in control group; $p = 0.894$).
						Operating time	No statistical difference between the two groups (498.5 ± 83.4 versus 525.2 ± 100.9 minutes; $p = 0.527$).
						Osteosynthesis time	Osteosynthesis time was significantly shorter in the computer-assisted group (10.1 ± 5.4 versus 18.2 ± 5.6 minutes; $p < 0.005$).
						Reconstruction time	Computer-assisted surgery shortened reconstruction time (16.4 ± 6.7 versus 38.5 ± 10.0 minutes; $p < 0.001$).
						Time to harvest	The time taken to saw and shape the transplant at the donor site was shorter using conventional surgery ($p < 0.005$).
Azuma et al. 2014, Japan	Mandibular reconstruction using plates prebent to fit rapid prototyping 3-dimensional printing models ameliorates contour deformity	Anatomical 3D printed models	Retrospective study	12 (12/0)	16 (16/0)	Final aesthetic result	The differential mandibular area and angle of the MRP group were significantly smaller than those of the conventional group ($p < 0.05$).
Ciocca et al. 2015, Italy	Accuracy of fibular sectioning and insertion into a rapid-prototyped bone plate, for mandibular reconstruction using	Surgical guides and templates; implants	Retrospective study	5 (5/0)	5 (5/0)	Measurement of axes and angles	No statistically significant difference was observed between the test and control groups, neither between lateral and vertical shift or mesial and distal sections.
						Position of the fibular units	A difference, even though not significant, in the lateral shift of the mesial and distal

First author, date, Country	Title	Applications	Study design	N° of patients in 3D group (mandibular/ maxillary cases)	N° of patients in control group (mandibular/ maxillary cases)	End-points	Outcomes
	CAD-CAM technology						positions of the fibular units was evident between groups.
Jiang et al. 2015, China	Functional evaluation of a CAD/CAM prosthesis for immediate defect repair after total maxillectomy: a case series of 18 patients with maxillary sinus cancer	Implants	Retrospective study	5 (0/5)	13 (0/13)	Final aesthetic result	Facial depression, and eyeball prolapse results showed improvements with prosthesis use at 1, 3, and 6 months after surgery ($p < 0.05$).
						Neurosensory disturbance	Speech intelligibility showed improvements with prosthesis use at 1, 3, and 6 months after surgery ($p < 0.05$). Swallowing function improved from level V to level II–IV with prosthesis use at 1, 3, and 6 months.
Mazzoni et al. 2013, Italy	Prosthetically guided maxillofacial surgery: evaluation of the accuracy of a surgical guide and custom-made bone plate in oncology patients after mandibular reconstruction	Anatomical 3D printed models; surgical guides and templates; implants	Prospective study	7 (7/0)	5 (5/0)	Measurement of axes and angles	No statistically significant difference was observed between the two groups regarding midline deviation, mandibular angle shift (except for the left angle shift on the lateral plane) and condylar position. With regard to angular deviation of the body axis, the data showed a significant difference in the arch deviation.
Modabber et al. 2012, Germany	Computer-assisted mandibular reconstruction with vascularized iliac crest bone graft	Anatomical 3D printed models; surgical guides and templates	Retrospective study	5 (5/0)	15 (15/0)	Accuracy of the harvested transplant	In the 3D group, the graft fitted perfectly into the mandibular defect without major adjustments for all patients. In the conventional surgery group, the harvested amount of bone exceeded the required amount by an average of 25.3 mm (range = 13.1–33.6 mm).

First author, date, Country	Title	Applications	Study design	N° of patients in 3D group (mandibular/ maxillary cases)	N° of patients in control group (mandibular/ maxillary cases)	End-points	Outcomes
						Ischemic time	The average ischemic time decreased by 15.6 minutes (range = 7.3–22.8 minutes) compared with that of conventional surgery.
Modabber et al. 2012, Germany	Evaluation of computer-assisted jaw reconstruction with free vascularized fibular flap compared with conventional surgery: a clinical pilot study	Anatomical 3D printed models; surgical guides and templates	Randomized prospective study	5 (2/3)	5 (4/1)	Accuracy of the harvested transplant	In the 3D group, there was no change between the defect size of the fibula and the necessary transplant size. In conventional surgery, a mean change of 1.92 cm occurred ($p = 0.001$).
						Ischemic time	Ischemic time was significantly shorter in the 3D group versus conventional surgery ($p = 0.014$).
						Time to harvest	Shaping procedure was significantly shorter in the 3D group versus conventional surgery ($p = 0.014$).
de Farias et al. 2014, Brazil	Use of prototyping in preoperative planning for patients with head and neck tumors	Anatomical 3D printed models	Randomized prospective study	17 (17/0)	20 (20/0)	Accuracy of the harvested transplant	Results showed a tendency to reduce the size of the bone flap taken for reconstruction with a remaining bone flap of 2.1 cm in the 3D group, ranging from 0–6 cm, and 8.7 cm in the control group, ranging from 5.5–13 cm.
						Final aesthetic result	Better aesthetic results were obtained in the 3D group than in the conventional surgery group.
						Osteosynthesis time	The osteosynthesis time was 30.42 minutes in the 3D group versus 86.66 minutes in the control group ($p = 0.001$).
						Reconstruction time	Reconstruction time was significantly shorter in the 3D group (43.70 minutes

First author, date, Country	Title	Applications	Study design	N° of patients in 3D group (mandibular/ maxillary cases)	N° of patients in control group (mandibular/ maxillary cases)	End-points	Outcomes
							versus 127.77 minutes in group B; $p = 0.001$).
						Screw insertion time	No statistical difference was observed in the duration of screw insertion (20 minutes in the 3D group versus 38.11 minutes in the control group).
						Time to harvest	No significant difference was observed (108.50 minutes in the 3D group and 141.10 minutes in the control group).
Sieira Gil et al. 2015, Spain	Surgical planning and microvascular reconstruction of the mandible with a fibular flap using computer-aided design, rapid prototype modelling, and precontoured titanium reconstruction plates: a prospective study	Anatomical 3D printed models; surgical guides and templates	Prospective study	10 (10/0)	10 (10/0)	Complications	Significant differences in the incidence of dental malocclusion ($p = 0.03$) and exposure of the titanium plate ($p = 0.009$) were observed, with higher incidences in the control group.
						Length of hospital stay	No significant difference was observed (18 days in the 3D group and 16 days in the control group; $p = 0.58$).
						Operating time	No significant difference in the operating time was found (357 minutes in the 3D group versus 421 minutes in the control group; $p = 0.14$).
						Reconstruction time	The mean operating time for reconstruction in the preoperative planning group was 135 minutes compared with 176 minutes in the conventional group ($p = 0.04$).
Sumida et al. 2015, Japan	Custom-made titanium devices as membranes for bone	Implants	Prospective study	13 (13/0)	13 (13/0)	Complications	No significant difference in the incidences of complications was observed ($p = 0.27$).

First author, date, Country	Title	Applications	Study design	N° of patients in 3D group (mandibular/ maxillary cases)	N° of patients in control group (mandibular/ maxillary cases)	End-points	Outcomes
	augmentation in implant treatment: clinical application and the comparison with conventional titanium mesh					Number of trays/screws used	The number of screws used was significantly fewer in the custom-made group than in the control group ($p < 0.01$).
						Operating time	The operation time of the custom-made group (75.4 ± 11.6 minutes) was significantly shorter than that of the conventional group (111.9 ± 17.8 minutes) ($p < 0.01$).
Tarsitano, et al. 2016, Italy	Is a computer-assisted design and computer-assisted manufacturing method for mandibular reconstruction economically viable?	Surgical guides and templates; implants	Prospective study	20 (20/0)	20 (20/0)	Cost	The money saved as a result of the time gained in the operating room was €3450. This cost corresponds approximately to the total price of the CAD-CAM surgery.
						Length of hospital stay	The mean overall lengths of hospital stay were 13.8 days for the CAD-CAM group and 17 days for the freehand group.
						Operating time	The mean operating time for the CAD-CAM group was 435 minutes, whereas that for the freehand group it was 550.5 minutes.
						Reconstruction time	The mean reconstructive time was 30.7 (range, 21–41) minutes for the 3D group and 63.8 (range, 45–79) minutes for the control group ($p = 0.041$).
Tarsitano, et al. 2016, Italy	Morphological results of customized microvascular mandibular	Surgical guides and templates; implants	Prospective study	30 (30/0)	30 (30/0)	Final aesthetic result	The mean differences registered between preoperative and postoperative CT scans were significantly better for the test group regarding chin protrusion ($p = 0.05$).

First author, date, Country	Title	Applications	Study design	N° of patients in 3D group (mandibular/ maxillary cases)	N° of patients in control group (mandibular /maxillary cases)	End-points	Outcomes
	reconstruction: a comparative study					Measurement of axes and angles	The mean differences registered between preoperative and postoperative CT scans were significantly better for the test group regarding mandibular angle ($p = 0.034$) and bigonial diameter ($p = 0.041$). No significant differences were registered for midline deviation ($p = 0.092$).
Zhang et al. 2011, <i>China</i>	Application of rapid prototyping for temporomandibular joint reconstruction	Anatomical 3D printed models	Prospective study	11 (11/0)	11 (11/0)	Operating time	The operative time was significantly longer in the control group than that in the 3D group (7.09 hours versus 5.67 hours, respectively; $p < 0.05$).

Table 2: End-points evaluated in the included studies and the outcomes observed

End-points	Number of studies	Statistical difference in favor of 3D printing	No statistical difference between the two groups
Operating time	5	Zhang et al. 2011 Sumida et al. 2015	Ayoub et al. 2014 Sieira Gil et al. 2015 Tarsitano et al. 2016a
Final aesthetic result	4	de Farias et al. 2014 Azuma et al. 2014 Jiang et al. 2015 Tarsitano et al. 2016b	
Accuracy of the harvested transplant	4	Modabber et al. 2012b Ayoub et al. 2014	de Farias et al. 2014 Modabber et al. 2012a
Reconstruction time	4	Ayoub et al. 2014 de Farias et al. 2014 Sieira Gil et al. 2015 Tarsitano, et al. 2016a	
Complications	3	Sieira Gil et al. 2015	Ayoub et al. 2014 Sumida et al. 2015 Sieira Gil et al. 2015
Ischemic time	3	Modabber et al. 2012a Modabber, et al. 2012b Ayoub et al. 2014	
Length of hospital stay	3		Ayoub et al. 2014 Sieira Gil et al. 2015 Tarsitano et al. 2016a
Measurement of axes and angles	3	Mazzoni et al. 2013 Tarsitano et al. 2016b	Mazzoni et al. 2013 Ciocca et al. 2015 Tarsitano, et al. 2016b
Time to harvest	3	Modabber et al. 2012b de Farias et al. 2014	Ayoub et al. 2014
Neurosensory disturbance	2	Al-Ahmad et al. 2013 Jiang et al. 2015	

End-points	Number of studies	Statistical difference in favor of 3D printing	No statistical difference between the two groups
Osteosynthesis time	2	de Farias et al. 2014 Ayoub et al. 2014	
Cost	1		Tarsitano, et al. 2016a
Intercondylar distance	1	Ayoub et al. 2014	
Length of stay in ICU	1		Ayoub et al. 2014
Number of trays/screws used	1	Sumida et al. 2015	
Position of the fibular units	1		Ciocca et al. 2015
Screw insertion time	1	de Farias et al. 2014	

*Some studies are indicated in both right-hand columns for some end-points because the results were significantly different for only some of the end-points evaluated.

Table 3: Risk of bias assessment (Cochrane risk of bias assessment tool)

Study	A	B	C	D	E	F	G
Ayoub et al. 2014	-	-	-	?	+	+	-
Sieira Gil et al. 2015	+	+	-	?	+	+	-
Sumida et al. 2015	+	?	-	?	+	+	-
Tarsitano, et al. 2016a	+	+	-	?	+	+	-

A: selection bias — random sequence generation; B: selection bias — allocation concealment; C: reporting bias — selective reporting; D: other sources of bias; E: performance bias — blinding (participants and personnel); F: detection bias — blinding (outcome assessment); G: incomplete outcome data