DR MUSTAFA MIAN (Orcid ID : 0000-0001-9318-2242)

Article type : Review Article

Title Page

Three-Dimensional Printing in Oral and Maxillofacial Surgery: Current Landscape and Future Directions

Running title: 3D printing in oral and maxillofacial surgery

Mustafa Mian [a,b*], Seth Delpachitra[c], David Ackland [d], Sarah Fink [e], Nathan Wang [e], George Dimitroulis [e,f]

a. The Alfred Hospital, Prahran, Victoria, Australia
b. Oral and Maxillofacial Surgery Unit, Royal Dental Hospital of Melbourne, Carlton, Victoria
c. Oral and Maxillofacial Surgery Unit, Monash Health, Melbourne, Victoria
d. Department of Biomedical Engineering, University of Melbourne, Parkville, Victoria, Australia
e. OMX Solutions, Melbourne, Victoria, Australia
f. Oral and Maxillofacial Surgery Unit, Epworth Healthcare, Melbourne, Victoria, Australia

*Corresponding author

E: mustafa.k.mian@outlook.com

Abstract

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/ORS.12658

Three-dimensional (3D) printing technology continues to develop at a rapid pace, with the potential to revolutionise multiple industries and fields including medicine. Oral and maxillofacial surgeons are particularly well placed to advance and integrate this technology into practice. This review provides a summary of 3D printing and discusses the current and future applications of this technology in oral and maxillofacial surgery, including the production of surgical planning models, training tools, cutting guides and personalised implants. While early research is promising, there still remains a paucity of large scale, well controlled clinical studies supporting the use of 3D printing technologies for many of these applications. There are also a number of other technical and regulatory challenges which will need to be addressed as this technology is taken up more widely.

Keywords

3D printing, 3D printed medical device, personalised implant, personalised surgery

Introduction

Three-dimensional (3D) printing technology, also known as additive manufacturing or rapid prototyping, refers to the process of constructing an object from a 3D digital model by successively adding material in layers. Since the introduction of 3D printing in the 1980's, applications for this technology have grown to include the automotive,[1] aerospace[2] and consumer goods industries[3] as well as the medical and dental sciences.[4] Innovations in medical 3D printing have attracted significant attention, especially within oral and maxillofacial surgery, [5] due to the ability to digitally recreate highly precise complex bony anatomy and produce patient-specific medical devices in a timely and cost-efficient manner.[6, 7] The objective of this review is to summarise 3D printing science and explore current and emerging applications of this technology in contemporary oral and maxillofacial surgery practice.

Overview of the 3D Printing Processes

Secure transfer, processing, and digital reconstruction of anatomic scans are the first steps in the process of 3D printing. Whilst this usually takes the form of a fine-slice computed tomogram (CT) due to superior hard tissue contrast and spatial resolution, magnetic resonance imaging (MRI) has been shown to be useful for virtual surgical planning in situations where ionising radiation may be contraindicated.[8, 9] More recently, cone-beam computed tomography (CBCT) has gained popularity in the diagnosis and management of conditions involving bone or teeth, due to good hard tissue image quality and lower radiation dose compared with conventional CT imaging.[10] Resulting imaging data is reconstructed in two-dimensional (2D) grey scale images that are usually saved in Digital Imaging and Communications in Medicine (DICOM) file format. Anatomical tissues are delineated by digital image segmentation, and a virtual 3D surface model is generated, usually in the format of a Standard Tessellation Language (STL) file. Accurate imaging and reconstruction of teeth can difficult via these modalities, partly due to image resolution but also the different radiodensities of enamel, dentine, restorative material and orthodontic brackets. While modified imaging protocols have been developed,[11] it is still commonplace to reimage the dentition using digital scanners, either intraorally or from dental casts and integrate these into the 3D STL reconstruction.[12] 3D reconstructions can then be used to design medical devices using specialised proprietary computer-aided design (CAD) software. Depending on the application, the oral and maxillofacial surgeon may be involved at this stage of design. The final model is exported to the printer, usually as an STL file, in order to generate a G-code which contains specific commands for printing. Depending on the application and material to be used, different 3D printing techniques can be utilised. The printed object will then usually undergo further post-printing processing, which can include removal of support structures, heat treatment, polishing and finishing, all of which can add significant time and cost to overall workflow. The final product may then undergo sterilisation depending on its planned use (Figure 1).

3D Printing Techniques and Materials

The most common 3D printing techniques employed in medicine are stereolithography, fused deposition modelling, powder bed fusion processes, and inkjet printing processes[13] (Figure 2). Available materials vary depending on the technique chosen (Table 1).

Stereolithography

Stereolithography is the earliest 3D printing technology described in medicine.[14] Liquid photopolymer in a tank is cured using UV laser, and as the build platform descends, the next layer is then cured. The main advantage of stereolithography is very high resolution, with smooth surface finishes, while the main disadvantages are that the process is slow, material choice is limited, and supporting structures must be manually removed post production.[15]

Fused Deposition Modelling

In fused deposition modelling, a continuous filament of thermoplastic polymer is heated to reach a semi-liquid state and then extruded in single plane. The build platform descends, and a new layer is deposited on top of the previous layer. Filaments fuse together and solidify at room temperature. The main advantages of fused deposition modelling are low start-up and production costs and high speed of production, while the main disadvantages include weak mechanical properties, a layer-by-layer appearance and retained support structures requiring removal.[16]

Powder Bed Processes

Thin layers of fine powders of thermoplastic, metal, glass or ceramic are fused together in powder bed fusion processes using high power laser beams, which move in a single plane. As the build platform descends, a new layer of powder is applied, and the layer-by-layer fusion process continues. Selective laser sintering is a variation of this process, where, powders are not fully melted, but instead heated sufficiently to allow individual grains to fuse. This can result in a porous material, or one that contains large numbers of microvoids.[17] In selective laser melting (SLM), powders are fully melted and fused together resulting in higher density materials and mechanical properties similar to the billet material.[18] Electron beam melting is similar to SLM except a high-powered electron beam is used to fuse powders under vacuum conditions.[19] Compared with other 3D printing techniques, powder bed processes have superior mechanical properties, making them most suitable for constructing maxillofacial and other biomedical implants.[20] The main disadvantages of powder bed techniques are that the process is slow, costly and usually requires large scale commercial equipment prohibiting its use for many smaller healthcare institutions.[16]

Inkjet Printing Processes

The two primary inkjet printing processes are binder jet printing and material jetting. Binder jet printing is similar to powder bed fusion; however, rather than a high-powered laser or electron beam fusing powders directly, a printer head ejects a binder, joining powders together. The build platform descends, a new layer of powder is applied, and the process continues. A wide range of materials, including metals, can be used and support structures are not required. The major disadvantages include poor mechanical properties compared powder bed technologies, making it less suitable for building implantable medical devices.[21] In material jetting, a printer head, moving in a single plane, sprays a photopolymer in layers, which is simultaneously cured by a UV lamp. The build platform gradually descends, as layers are deposited one on top of the other. Supporting gels can simultaneously printed for removal post-production. Material jetting can use different materials for different parts of the object. Major disadvantages include high cost and a limited range of photopolymerisable materials available.[22]

3D Printing in Oral and Maxillofacial Surgery

Surgical Planning and Reference

3D printing in maxillofacial surgery was popularised in the 1990's, primarily for printing of anatomical biomodels to assist in surgical planning of patients with severe craniomaxillofacial deformities.[23] The use of biomodels has since spread to other domains of oral and maxillofacial surgery, including orthognathic surgery,[24] head and neck oncology,[25] and complex maxillofacial trauma.[26] Both hard and soft tissue modelling is possible, with the ability to colourise pathology or other structures of interest (Figure 3).[27] 3D printed models can be used to enhance the interpretation of volumetric image data, optimise surgical planning, as a reference during surgery, and for presurgical adaptation of hardware.[28] Importantly, 3D printed models are also highly accessible, as they are generally not subject to medical device regulation. High level evidence for the use of 3D printed models is scarce, in part due to the tendency for most centres to reserve 3D printing for highly complex cases only. One randomised controlled trial used 3D models to preoperatively simulate surgery in patients with head and neck tumours. The authors demonstrated reduced surgical time, reduced donor site morbidity and improved patient reported cosmesis, compared with standard preoperative planning.[22] Questionnaire based studies in surgeons using 3D models to plan craniomaxillofacial surgery have reported similar benefits subjectively.[29, 30]

Today surgical planning is increasingly being completed digitally via virtual surgical planning (VSP) technologies. VSP shares many of the benefits of 3D printed models including detailed visualisation of the craniomaxillofacial complex and the ability to simulate surgeries preoperatively, however VSP is much more accessible and often more versatile compared to 3D printing, and avoids the cost and time associated with 3D printed models.[31] As VSP technologies continue to be taken up by oral and maxillofacial surgeons, it likely that 3D printed models for planning or surgical reference will become less common.

Custom Surgical Guides

Custom surgical guides are employed frequently across multiple surgical specialties to allow for more accurate surgical resections, osteotomies or implant placement, and to reduce surgical time.[5] Benefits of 3D printing surgical guides include better integration with virtual surgical planning protocols, improved versatility and lower production cost compared with conventional fabrication processes.[32] Two randomised controlled trials have shown increased accuracy of dental implant placement and improved clinical outcomes using 3D printed guides compared to unguided surgery, with other additional advantages including avoidance of raising a mucoperiosteal flap, and the possibility of immediate implant loading using a prefabricated fixed prosthesis based on planned implant position.[33, 34]

3D printed occlusal splints and cutting guides are also used widely in orthognathic surgery. A number of small retrospective cohort studies have shown that the use of 3D printed occlusal splints achieves similar surgical accuracy compared to facebow and model surgery, with a possible additional benefit in cases with a high degree of left-right asymmetry or an unstable condylar position.[35, 36] Despite increased uptake, there remains a paucity of high-quality evidence investigating the efficacy of cutting guides in orthognathic surgery, with most publications either presenting surgical protocols or a case reports.[37-42] One recent randomised trial of 21 patients demonstrated improved accuracy and reduced surgical time for bimaxillary orthognathic surgery using virtual surgical planning, 3D printed splints and prebending bone plates compared with conventional treatment.[43] Multiple prospective cohort studies have supported these findings.[44, 45] Another randomised, split-mouth trial showed improved neurosensory function associated with 3D printed cutting guides compared with unguided surgery in bilateral sagittal split ramus osteotomies, however this study was limited by a small sample size and short follow-up period.[46]

Surgical cutting guides are also used for bone grafts in reconstructive surgery of the maxillofacial complex. One common application is for segmental mandibular reconstructions with vascularised free flaps following severe trauma or after resection of pathology. In these cases, cutting guides can be used for both maxillofacial and donor site osteotomies (Figure 4). In oral and maxillofacial surgery, free fibula flap reconstructions are the most common and well researched, with one small randomised controlled trial and a number cohort and case control studies showing that use of 3D printed cutting guides for maxillofacial reconstruction results in reduced ischemic time, reduced surgical time and improved surgical accuracy.[47-55] A randomised controlled trial of 20 patients found similar benefits using 3D printed cutting guides in vascularised iliac crest graft mandibular reconstructions.[56]

Virtual treatment planning and 3D printed cutting guides have been widely in calvarial vault remodelling for craniosynostosis. In these cases, templates and cutting guides based on idealised craniofacial morphology can be 3D printed preoperatively instead of relying on the surgeon's subjective perception of normal morphology intraoperatively. A number of retrospective case-control studies have shown that the use of 3D printed templates for calvarial reconstruction results in improved post-operative outcomes and shorter surgical times.[57, 58] Further larger scale, prospective studies would help validate the benefits of 3D printed surgical guides in this context.

Personalised Implants and Prostheses

Personalised medical implants may be patient-specific whereby they are custom made for sole use in a particular patient, or patient-matched whereby an implant is matched to a patient's anatomy within a specified design envelope. This distinction is highly relevant to the regulatory and legal requirements of medical devices in different jurisdictions. In the UK, under the European Medical Device Regulations,[59] patient-matched implants, which are typically mass produced, are subject to a higher level of regulation, requiring manufacturers to have a formal quality management system and certification mark. This review refers to patient-specific and patient-matched implants together as "personalised implants".

Personalised implants are being used across oral and maxillofacial surgery to improve surgical outcomes for routine surgeries but also to treat complex conditions which would be otherwise unamenable to conventional therapies. Titanium remains the metal of choice for 3D printing maxillofacial implants and has wide regulatory approval. It has the advantages of high strength, good biocompatibility, and the potential for osteointegration.[60] To date, the main non-resorbable polymers used in maxillofacial implants are high molecular weight polyethylene and polyether ether ketone (PEEK), which are chosen due to similar strength and elasticity to bone.[61] The manufacture of PEEK implants has been previously limited mainly to subtractive manufacturing processes. More recently PEEK 3D printing has allowed construction of more complex geometry, with hollow or lightweight biomimicking designs that cannot be manufactured using alternative technologies.[62] A disadvantage of both polyethylene and PEEK is that they have potentially higher rates of infection and foreign body reaction compared with titanium.[63] A limited number of resorbable implant materials are also available such as poly D, L-lactic acid (PDLLA) and poly lactic-co-glycolic acid (PLGA) which are typically reserved for paediatric patients.[64]. Achieving approval for other new materials remains a major regulatory challenge.

Surgical plates and screws are used to stabilise bone segments in oral and maxillofacial surgery. Conventionally, surgical plates are mass-produced and require manual manipulation in order to match bony anatomy intraoperatively. This can be time consuming, especially for inexperienced surgeons.[65] Repeat bending of surgical plates can alter the mechanical properties resulting in an increased risk of complications, such as plate fracture.[66] 3D printed, personalised surgical plates and screws attempt to address these issues (Figure 5). A number of small, retrospective studies have shown personalised 3D printed surgical plates to significantly reduce total surgical time and improve surgical accuracy in head and neck cancer surgery and orthognathic surgery.[67-70]

In oral and maxillofacial surgery, personalised reconstructive implants have been used to successfully restore form and function in cases that may not otherwise be amenable to conventional treatment. Benefits of personalised reconstructive implants in these cases include improved surgical accuracy, improved cosmesis, the ability to restore large and geometrically complex anatomical defects, reduction in operative times and the ability to perform resection and reconstruction in one step.[61, 71] Currently, evidence is limited to proof-of-concept studies and case reports. Some common applications of personalised implants include cranioplasty and restoration of large maxillary, mandibular and zygomatic defects.[72-78]

Orbital wall reconstructions have conventionally been managed by intraoperative shaping of autologous bone grafts or by manual manipulation of stock implants. Especially in large defects or in revision surgery, this can be difficult because of the complex 3D anatomy of the orbit and because slight malpositioning of the graft or mesh can result in enophthalmos or other complications.[79] Prebending stock implants preoperatively using 3D printed models has already been to shown to improve postoperative outcomes and reduce total surgical time in a several cohort studies,[79, 80] however evidence for personalised 3D printed orbital implants (Figure 6) remains limited. One small randomised controlled trial demonstrated reduced postoperative enophthalmos associated with 3D printed titanium mesh compared with intraoperative manipulation of stock mesh, however this study was limited by a small sample size.[81] Larger scale studies are required to support these findings and outline a future role for 3D printing technology in orbital reconstruction.

Until recently, a major shortcoming of TMJ replacement surgery has been the limitations of stock TMJ components, which may not conform well to the wide range of jaw morphologies and hard tissue pathologies that patients requiring TMJ replacement may present with. Advancements in 3D manufacturing technology have facilitated the development of personalised TMJ implants (Figure 7) which are more anatomically acceptable, especially in cases of severely degenerated or distorted mandibular condyles or in cases of significant skeletal malocclusion.[82-84] Preliminary outcomes for 3D printed TMJ implants are promising[84, 85] with further larger scale, comparative studies required in order to support their use over alternative technologies.

While endosseous dental implants provide a highly predictable solution for prosthetic rehabilitation in cases of partial or total edentulism,[86-89] bone volume and quality can limit their application.[90-92] An emerging role for 3D printing is in the fabrication of personalised subperiosteal implants for prosthetic rehabilitation in these cases (Figure 8). Subperiosteal implants were popular from the 1940's to the 1980s,[93] however suffered from a number of major shortcomings, including a relatively morbid impression stage requiring extensive surgical skeletisation, and complex laboratory construction. 3D printed subperiosteal implants allow for single step prosthetic rehabilitation, without the need for complex adjunctive bone augmentation procedures which may otherwise be required.[92] A limited number of outcome studies have been published on 3D printed subperiosteal implants, reporting failure rates of 0-2.1% per year.[94, 95] However, these are limited by small, highly selective samples and short follow up periods. Larger prospective studies with longer follow up periods are required prior to wider uptake.

A recurring limitation to current research in 3D printed maxillofacial implants is the absence of large-scale clinical trials, which are difficult or impossible to conduct for many highly bespoke devices. An emerging solution is through the use of personalised musculoskeletal models and simulations, which can be used for evaluating the functional performance of an implant prior to printing and implantation. In oral and maxillofacial surgery, this is particularly important for implants that are subject to masticatory forces and are subsequently at high risk of mechanical failure.[96] Musculoskeletal models can be used to simulate muscle and joint loading on a subject-specific basis in order to evaluate the load-response of the implant and assess the effect of different design parameters, including implant size, shape and material properties. They also facilitate assessment of the influence of implant malposition, screw fixation and other surgical variables on implant function and device longevity.[83] In the future, these processes may give clinicians more confidence in the safety and efficacy of personalised implants and eventually form part of the regulatory approval process for these devices.

Education and Training

3D printed models and devices can be used to teach anatomy and for practicing procedures on patient-specific replications with a high degree of anatomical and structural fidelity consistent with live tissue and important disease processes. As a tool for anatomy education, 3D printed models have the advantage of being cheaper than cadaveric material, show anatomical variation and are not subject to legal barriers relating to transportation, importation and licensing, making them an attractive option for medical educators. One randomised controlled trial showed improved learning efficiency using 3D printed skulls compared with cadaveric skulls and atlases in a cohort of medical students.[97]

3D printed models are also being used for procedural training across a range of oral and maxillofacial surgery procedures, including third molar surgery, maxillary sinus lifts, mandibular reconstructions, skull base surgery, craniofacial surgery and facial trauma[98-103] with many more applications feasible. Of the handful of studies directly comparing 3D printed models of head and neck structures to corresponding cadaveric and animal specimens, all report realistic mechanical and handling properties.[104-107] Other advantages of 3D printed models compared with existing simulation technologies include lower cost and greater customisability.[105] Currently, 3D printed models for surgical training in oral and maxillofacial surgery have mainly focussed on replicating bone, with polycarbonate materials probably representing the best compromise between anatomical and mechanical accuracy, visual and surface appearance and production cost.[104]

Tissue Engineering and 3D Bioprinting

An emerging application for 3D printing is in tissue engineering and regeneration, with the goal of developing personalised, living tissue constructs for reconstructive surgery, without the donor site morbidity associated with autogenous tissue grafts. The technical aspects of 3D printing biological tissues is outside the scope of this review and have been described in detail previously.[108-111] Briefly, there are two main methods commonly employed: printing acellular scaffolds which are later seeded with cells prior to implantation, or printing living tissue with spatial control of the functional components, the latter termed “3D bioprinting”.[112]

Early studies using 3D printed bone scaffolds for treating calvarial, mandibular and maxillary bone defects in animal models, suggest improved angiogenesis, bony ingrowth and bone regeneration compared to non-biological controls.[113-116] These findings have also been replicated using direct, in-situ, bioprinting techniques.[117] 3D printing other tissue types such as skin[118-122] and cartilage[123-126], similarly show promise, however research in this field is still in the preclinical phase.

Conclusion

There is now a wide range of applications for 3D printing in oral and maxillofacial surgery including in the production of surgical planning models, training tools, cutting guides and personalised implants. As useability and accessibility increase, it is likely that oral and maxillofacial surgeons will engage more with these technologies. Current technical challenges include increasing the quantity and diversity of materials available, which to date have been limited by the need to use proprietary materials from the printer manufacturer, and challenges in gaining regulatory approval for the use of new biocompatible materials.[127] Also, advancements in post-printing processing, especially in the removal of support structures, will assist in speeding up the manufacturing process.[128] In oral and maxillofacial surgery, there remains a paucity of high quality, well controlled studies demonstrating the benefits of 3D printing techniques over conventional therapies. This may be offset in some ways through patient-specific musculoskeletal modelling and simulations, which are becoming increasingly advanced and computationally efficient. Simultaneously, a number of past and current applications for 3D printing, for example 3D models for preoperative planning, may become less common, as they are superseded by other emerging technologies such as virtual treatment planning and virtual reality simulations. Regulatory bodies must continue to balance advancement and access of 3D printing technologies for personalised surgery with the need to protect the public from bespoke devices without adequate testing or evaluation.

Conflict of interests

The senior author (G.D.) holds shares in OMX Solutions Pty Ltd.

Co-authors (S.F. and N.W.) are employed by OMX Solutions Pty Ltd.

Acknowledgements

We grateful to staff from OMX solutions Pty Ltd. for providing the images used in this review.

References

1. Srrehitha V. Impact of 3D Printing in Automotive Industries International Journal of Mechanical and Production Engineering 2017;5:91-94

2. Uriondo A, Esperon-Miguez M, Perinpanayagam S. The present and future of additive manufacturing in the aerospace sector: A review of important aspects. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 2015;229:2132-2147

3. Petrick IJ, Simpson TW. 3D Printing Disrupts Manufacturing: How Economies of One Create New Rules of Competition. Research-Technology Management 2013;56:12-16 https://doi.org/10.5437/08956308X5606193.

4. Ventola CL. Medical Applications for 3D Printing: Current and Projected Uses. P T 2014;39:704-711 https://pubmed.ncbi.nlm.nih.gov/25336867 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4189697/.

5. Tack P, Victor J, Gemmel P, Annemans L. 3D-printing techniques in a medical setting: a systematic literature review. Biomed Eng Online 2016;15:115 https://www.ncbi.nlm.nih.gov/pubmed/27769304.

6. Choi JW, Kim N. Clinical application of three-dimensional printing technology in craniofacial plastic surgery. Arch Plast Surg 2015;42:267-277 https://www.ncbi.nlm.nih.gov/pubmed/26015880.

7. Thomas D. Costs, Benefits, and Adoption of Additive Manufacturing: A Supply Chain Perspective. Int J Adv Manuf Technol 2016;85:1857-1876 https://pubmed.ncbi.nlm.nih.gov/28747809 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5524380/.

8. Hermans R, De Keyzer F, Vandecaveye V. Imaging Techniques. In: Hermans R, ed. Head and Neck Cancer Imaging. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006:31-42.

9. Suchyta MA, Gibreel W, Hunt CH, Gorny KR, Bernstein MA, Mardini S. Using Black Bone Magnetic Resonance Imaging in Craniofacial Virtual Surgical Planning: A Comparative Cadaver Study. Plastic and Reconstructive Surgery 2018;141https://journals.lww.com/plasreconsurg/Fulltext/2018/06000/Using_Black_Bone_Magnetic_Resonance_Imaging_in.25.aspx.

10. Kiljunen T, Kaasalainen T, Suomalainen A, Kortesniemi M. Dental cone beam CT: A review. Phys Med 2015;31:844-860 https://www.ncbi.nlm.nih.gov/pubmed/26481816.

11. Swennen GR, Mommaerts MY, Abeloos J, De Clercq C, Lamoral P, Neyt N, Casselman J, Schutyser F. A cone-beam CT based technique to augment the 3D virtual skull model with a detailed dental surface. International journal of oral and maxillofacial surgery 2009;38:48-57

12. Ayoub AF, Rehab M, O'Neil M, Khambay B, Ju X, Barbenel J, Naudi K. A novel approach for planning orthognathic surgery: the integration of dental casts into three-dimensional printed mandibular models. International journal of oral and maxillofacial surgery 2014;43:454-459

13. Chae M, Rozen W, McMenamin P, Findlay M, Spychal R, Hunter-Smith D. Emerging Applications of Bedside 3D Printing in Plastic Surgery. Frontiers in surgery 2015;2:25

14. Melchels FPW, Feijen J, Grijpma DW. A review on stereolithography and its applications in biomedical engineering. Biomaterials 2010;31:6121-6130 http://www.sciencedirect.com/science/article/pii/S0142961210005661.

15. Prakash KS, Nancharaih T, Rao VVS. Additive Manufacturing Techniques in Manufacturing -An Overview. Materials Today: Proceedings 2018;5:3873-3882 http://www.sciencedirect.com/science/article/pii/S2214785317329152.

16. Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Composites Part B: Engineering 2018;143:172-196 http://www.sciencedirect.com/science/article/pii/S1359836817342944.

17. Flodberg G, Pettersson H, Yang L. Pore analysis and mechanical performance of selective laser sintered objects. Additive Manufacturing 2018;24:307-315 http://www.sciencedirect.com/science/article/pii/S2214860418306699.

18. Olakanmi EO, Cochrane RF, Dalgarno KW. A review on selective laser sintering/melting (SLS/SLM) of aluminium alloy powders: Processing, microstructure, and properties. Progress in Materials Science 2015;74:401-477 http://www.sciencedirect.com/science/article/pii/S0079642515000389.

19. Körner C. Additive manufacturing of metallic components by selective electron beam melting — a review. International Materials Reviews 2016;61:361-377 https://doi.org/10.1080/09506608.2016.1176289.

20. Ni J, Ling H, Zhang S, Wang Z, Peng Z, Benyshek C, Zan R, Miri AK, Li Z, Zhang X, Lee J, Lee KJ, Kim HJ, Tebon P, Hoffman T, Dokmeci MR, Ashammakhi N, Li X, Khademhosseini A. Three-dimensional printing of metals for biomedical applications. Materials Today Bio 2019;3:100024 http://www.sciencedirect.com/science/article/pii/S259000641930050X.

21. Dini F, Ghaffari SA, Jafar J, Hamidreza R, Marjan S. A review of binder jet process parameters; powder, binder, printing and sintering condition. Metal Powder Report 2020;75:95-100 http://www.sciencedirect.com/science/article/pii/S0026065719301705.

22. Kim GB, Lee S, Kim H, Yang DH, Kim Y-H, Kyung YS, Kim C-S, Choi SH, Kim BJ, Ha H, Kwon SU, Kim N. Three-Dimensional Printing: Basic Principles and Applications

in Medicine and Radiology. Korean journal of radiology 2016;17:182-197
https://www.ncbi.nlm.nih.gov/pubmed/26957903
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4781757/.

23. Mankovich NJ, Cheeseman AM, Stoker NG. The display of three-dimensional anatomy with stereolithographic models. J Digit Imaging 1990:200

24. Lin H-H, Lonic D, Lo L-J. 3D printing in orthognathic surgery − A literature review. Journal of the Formosan Medical Association 2018;117:547-558
http://www.sciencedirect.com/science/article/pii/S0929664617304138.

25. de Farias TP, Dias FL, Galvao MS, Boasquevisque E, Pastl AC, Albuquerque Sousa B. Use of prototyping in preoperative planning for patients with head and neck tumors. Head & neck 2014;36:1773-1782

26. King BJ, Park EP, Christensen BJ, Danrad R. On-Site 3-Dimensional Printing and Preoperative Adaptation Decrease Operative Time for Mandibular Fracture Repair. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons 2018;76:1950.e1951-1950.e1958

27. Suomalainen A, Stoor P, Mesimäki K, Kontio RK. Rapid prototyping modelling in oral and maxillofacial surgery: A two year retrospective study. Journal of clinical and experimental dentistry 2015;7:e605-e612 https://www.ncbi.nlm.nih.gov/pubmed/26644837
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4663063/.

28. Shilo D, Emodi O, Blanc O, Noy D, Rachmiel A. Printing the Future-Updates in 3D Printing for Surgical Applications. Rambam Maimonides medical journal 2018;9:e0020
https://www.ncbi.nlm.nih.gov/pubmed/30089093
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6115481/.

29. D'Urso PS, Barker TM, Earwaker WJ, Bruce LJ, Atkinson RL, Lanigan MW, Arvier JF, Effeney DJ. Stereolithographic biomodelling in cranio-maxillofacial surgery: a prospective trial. Journal of Cranio-Maxillofacial Surgery 1999;27:30-37
http://www.sciencedirect.com/science/article/pii/S1010518299800079.

30. Dumas BM, Nava A, Law HZ, Smartt J, Derderian C, Seaward JR, Kane AA, Hallac RR. Three-Dimensional Printing for Craniofacial Surgery: A Single Institution's 5-Year Experience. The Cleft palate-craniofacial journal : official publication of the American Cleft Palate-Craniofacial Association 2019;56:729-734

31. Hua J, Aziz S, Shum JW. Virtual Surgical Planning in Oral and Maxillofacial Surgery. Oral and maxillofacial surgery clinics of North America 2019;31:519-530

32. Jensen L, Lovschall C, thomsen a, Valentin G, Risør B, Benguria-Arrate G, Vasco L, Gutiérrez-Ibarluzea I, Ercevic D. Custom-made or customisable 3D printed implants and cutting guides versus non3D printed standard implants and cutting guides for improving outcome in patients undergoing knee, maxillofacial, or cranial surgery, 2019.

33. Van de Velde T, Sennerby L, De Bruyn H. The clinical and radiographic outcome of implants placed in the posterior maxilla with a guided flapless approach and immediately restored with a provisional rehabilitation: a randomized clinical trial. Clinical oral implants research 2010;21:1223-1233

34. Vercruyssen M, Cox C, Coucke W, Naert I, Jacobs R, Quirynen M. A randomized clinical trial comparing guided implant surgery (bone- or mucosa-supported) with mental navigation or the use of a pilot-drill template. J Clin Periodontol 2014;41:717-723

35. Cousley RRJ, Bainbridge M, Rossouw PE. The accuracy of maxillary positioning using digital model planning and 3D printed wafers in bimaxillary orthognathic surgery. J Orthod 2017;44:256-267

36. Park JH, Lee Y-B, Kim SY, Kim HJ, Jung Y-S, Jung H-D. Accuracy of modified CAD/CAM generated wafer for orthognathic surgery. PLoS One 2019;14:e0216945 https://doi.org/10.1371/journal.pone.0216945.

37. Edwards SP. Computer-assisted craniomaxillofacial surgery. Oral and maxillofacial surgery clinics of North America 2010;22:117-134

38. Hernandez-Alfaro F, Guijarro-Martinez R, Molina-Coral A, Badia-Escriche C. "Surgery first" in bimaxillary orthognathic surgery. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons 2011;69:e201-207

39. Marlière DAA, Salazar DFS, Gonçalves TOF, Silveira HM. Virtual surgical planning for bimaxillary orthognathic surgery simultaneously associated with subapical mandibular and maxillary segmental osteotomies: a case report. International journal of oral and maxillofacial surgery 2019;48:124 https://doi.org/10.1016/j.ijom.2019.03.383.

40. Swennen GR, Mollemans W, Schutyser F. Three-dimensional treatment planning of orthognathic surgery in the era of virtual imaging. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons 2009;67:2080-2092

41. Uribe F, Janakiraman N, Shafer D, Nanda R. Three-dimensional cone-beam computed tomography-based virtual treatment planning and fabrication of a surgical splint

for asymmetric patients: surgery first approach. Am J Orthod Dentofacial Orthop 2013;144:748-758
42. Xia JJ, Gateno J, Teichgraeber JF. New clinical protocol to evaluate craniomaxillofacial deformity and plan surgical correction. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons 2009;67:2093-2106
43. Schneider D, Kammerer PW, Hennig M, Schon G, Thiem DGE, Bschorer R. Customized virtual surgical planning in bimaxillary orthognathic surgery: a prospective randomized trial. Clin Oral Investig 2019;23:3115-3122
44. Steinhuber T, Brunold S, Gartner C, Offermanns V, Ulmer H, Ploder O. Is Virtual Surgical Planning in Orthognathic Surgery Faster Than Conventional Planning? A Time and Workflow Analysis of an Office-Based Workflow for Single- and Double-Jaw Surgery. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons 2018;76:397-407
45. Wrzosek MK, Peacock ZS, Laviv A, Goldwaser BR, Ortiz R, Resnick CM, Troulis MJ, Kaban LB. Comparison of time required for traditional versus virtual orthognathic surgery treatment planning. International journal of oral and maxillofacial surgery 2016;45:1065-1069 https://doi.org/10.1016/j.ijom.2016.03.012.
46. Al-Ahmad HT, M Saleh MW, Hussein AuM. 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 and Computer Assisted Surgery 2013;9:134-141 https://doi.org/10.1002/rcs.1474.
47. Bao T, He J, Yu C, Zhao W, Lin Y, Wang H, Liu J, Zhu H. Utilization of a pre-bent plate-positioning surgical guide system in precise mandibular reconstruction with a free fibula flap. Oral Oncol 2017;75:133-139
48. Modabber A, Legros C, Rana M, Gerressen M, Riediger D, Ghassemi A. 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 2012;8:215-220
49. Schepers RH, Raghoebar GM, Vissink A, Stenekes MW, Kraeima J, Roodenburg JL, Reintsema H, Witjes MJ. Accuracy of fibula reconstruction using patient-specific CAD/CAM reconstruction plates and dental implants: A new modality for functional reconstruction of mandibular defects. Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery 2015;43:649-657

50. Toto JM, Chang EI, Agag R, Devarajan K, Patel SA, Topham NS. Improved operative efficiency of free fibula flap mandible reconstruction with patient-specific, computer-guided preoperative planning. Head & neck 2015;37:1660-1664
51. Bosc R, Hersant B, Carloni R, Niddam J, Bouhassira J, De Kermadec H, Bequignon E, Wojcik T, Julieron M, Meningaud JP. Mandibular reconstruction after cancer: an in-house approach to manufacturing cutting guides. International journal of oral and maxillofacial surgery 2017;46:24-31
52. Ciocca L, Marchetti C, Mazzoni S, Baldissara P, Gatto MR, Cipriani R, Scotti R, Tarsitano A. 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 : official publication of the European Association for Cranio-Maxillo-Facial Surgery 2015;43:28-33
53. Hanasono MM, Skoracki RJ. Computer-assisted design and rapid prototype modeling in microvascular mandible reconstruction. Laryngoscope 2013;123:597-604
54. Sieira Gil R, Roig AM, Obispo CA, Morla A, Pages CM, Perez JL. 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. Br J Oral Maxillofac Surg 2015;53:49-53
55. Ren W, Gao L, Li S, Chen C, Li F, Wang Q, Zhi Y, Song J, Dou Z, Xue L, Zhi K. Virtual Planning and 3D printing modeling for mandibular reconstruction with fibula free flap. Medicina oral, patologia oral y cirugia bucal 2018;23
56. Ayoub N, Ghassemi A, Rana M, Gerressen M, Riediger D, Holzle F, Modabber A. Evaluation of computer-assisted mandibular reconstruction with vascularized iliac crest bone graft compared to conventional surgery: a randomized prospective clinical trial. Trials 2014;15:114 https://www.ncbi.nlm.nih.gov/pubmed/24716651.
57. Andrew TW, Baylan J, Mittermiller PA, Cheng H, Johns DN, Edwards MSB, Cheshier SH, Grant GA, Lorenz HP. Virtual Surgical Planning Decreases Operative Time for Isolated Single Suture and Multi-suture Craniosynostosis Repair. Plastic and reconstructive surgery Global open 2018;6:e2038-e2038 https://www.ncbi.nlm.nih.gov/pubmed/30656118 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6326593/.
58. Khechoyan DY, Saber NR, Burge J, Fattah A, Drake J, Forrest CR, Phillips JH. Surgical outcomes in craniosynostosis reconstruction: the use of prefabricated templates in cranial vault remodelling. J Plast Reconstr Aesthet Surg 2014;67:9-16

59. The European Parliament and the Council of the European Union. Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices, amending Directive 2001/83/EC, Regulation (EC) No 178/2002 and Regulation (EC) No 1223/2009 and repealing Council Directives 90/385/EEC and 93/42/EEC. European Union 2017.

60. Acero J, Calderon J, Salmeron JI, Verdaguer JJ, Concejo C, Somacarrera ML. The behaviour of titanium as a biomaterial: microscopy study of plates and surrounding tissues in facial osteosynthesis. Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery 1999;27:117-123

61. Oh J. Recent advances in the reconstruction of cranio-maxillofacial defects using computer-aided design/computer-aided manufacturing. Maxillofacial plastic and reconstructive surgery 2018;40:2-2 https://www.ncbi.nlm.nih.gov/pubmed/29430438 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5797724/.

62. Thieringer FM, Sharma N, Mootien A, Schumacher R, Honigmann P. Patient Specific Implants from a 3D Printer – An Innovative Manufacturing Process for Custom PEEK Implants in Cranio-Maxillofacial Surgery. In: Meboldt M, Klahn C, eds. Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications - AMPA2017. Cham: Springer International Publishing, 2018:308-315.

63. Kwarcinski J, Boughton P, Ruys A, Doolan A, van Gelder J. Cranioplasty and Craniofacial Reconstruction: A Review of Implant Material, Manufacturing Method and Infection Risk. Applied Sciences 2017;7:276 https://app.dimensions.ai/details/publication/pub.1084434841 https://www.mdpi.com/2076-3417/7/3/276/pdf.

64. Neumann A, Kevenhoerster K. Biomaterials for craniofacial reconstruction. GMS current topics in otorhinolaryngology, head and neck surgery 2009;8:Doc08-Doc08 https://www.ncbi.nlm.nih.gov/pubmed/22073101 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3199817/.

65. Yang W-f, Choi WS, Leung YY, Curtin JP, Du R, Zhang C-y, Chen X-s, Su Y-x. Three-dimensional printing of patient-specific surgical plates in head and neck reconstruction: A prospective pilot study. Oral Oncology 2018;78:31-36 http://www.sciencedirect.com/science/article/pii/S1368837518300137.

66. Martola M, Lindqvist C, Hänninen H, Al-Sukhun J. Fracture of titanium plates used for mandibular reconstruction following ablative tumor surgery. Journal of Biomedical

Materials Research Part B: Applied Biomaterials 2007;80B:345-352 https://doi.org/10.1002/jbm.b.30603.
67. Mazzoni S, Bianchi A, Schiariti G, Badiali G, Marchetti C. Computer-Aided Design and Computer-Aided Manufacturing Cutting Guides and Customized Titanium Plates Are Useful in Upper Maxilla Waferless Repositioning. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons 2015;73:701-707 http://www.sciencedirect.com/science/article/pii/S0278239114016279.
68. Mazzoni S, Marchetti C, Sgarzani R, Cipriani R, Scotti R, Ciocca L. Prosthetically Guided Maxillofacial Surgery: Evaluation of the Accuracy of a Surgical Guide and Custom-Made Bone Plate in Oncology Patients after Mandibular Reconstruction. Plast Reconstr Surg 2013;131https://journals.lww.com/plasreconsurg/Fulltext/2013/06000/Prosthetically_Guided_Maxillofacial_Surgery__.20.aspx.
69. Suojanen J, Leikola J, Stoor P. The use of patient-specific implants in orthognathic surgery: A series of 32 maxillary osteotomy patients. J Cranio Maxill Surg 2016;44:1913-1916 http://www.sciencedirect.com/science/article/pii/S101051821630213X.
70. Ciocca L, Mazzoni S, Fantini M, Persiani F, Marchetti C, Scotti R. CAD/CAM guided secondary mandibular reconstruction of a discontinuity defect after ablative cancer surgery. Journal of Cranio-Maxillofacial Surgery 2012;40:e511-e515 http://www.sciencedirect.com/science/article/pii/S1010518212000911.
71. Peel S, Bhatia S, Eggbeer D, Morris DS, Hayhurst C. Evolution of design considerations in complex craniofacial reconstruction using patient-specific implants. Proc Inst Mech Eng H 2017;231:509-524
72. De La Peña A, De La Peña-Brambila J, Pérez-De La Torre J, Ochoa M, Gallardo GJ. Low-cost customized cranioplasty using a 3D digital printing model: a case report. 3D printing in medicine 2018;4:4-4 https://www.ncbi.nlm.nih.gov/pubmed/29782609 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5954791/.
73. Morales-Gomez JA, Garcia-Estrada E, Leos-Bortoni JE, Delgado-Brito M, Flores-Huerta LE, De La Cruz-Arriaga AA, Torres-Diaz LJ, de Leon ARM. Cranioplasty with a low-cost customized polymethylmethacrylate implant using a desktop 3D printer. J Neurosurg 2018:1-7
74. Msallem B, Beiglboeck F, Honigmann P, Jaquiéry C, Thieringer F. Craniofacial Reconstruction by a Cost-Efficient Template-Based Process Using 3D Printing. Plastic and reconstructive surgery Global open 2017;5:e1582-e1582 https://www.ncbi.nlm.nih.gov/pubmed/29263977

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5732683/.
75. Vosselman N, Merema BJ, Schepman KP, Raghoebar GM. Patient-specific sub-periosteal zygoma implant for prosthetic rehabilitation of large maxillary defects after oncological resection. International journal of oral and maxillofacial surgery 2019;48:115-117
76. Huang S-N, Shie M-Y, Shen Y, Hsu J-T, Huang HL, Fuh L-J. Biomechanical Assessment of Design Parameters on a Self-Developed 3D-Printed Titanium-Alloy Reconstruction/Prosthetic Implant for Mandibular Segmental Osteotomy Defect. Metals 2019;9:597
77. U V, Mehrotra D, Howlader D, Singh PK, Gupta S. Patient Specific Three-Dimensional Implant for Reconstruction of Complex Mandibular Defect. J Craniofac Surg 2019;30https://journals.lww.com/jcraniofacialsurgery/Fulltext/2019/06000/Patient_Specific_Three_Dimensional_Implant_for.97.aspx.
78. Meena V, Rattan V, Luthra G. Development of a custom zygomatic implant using metal sintering. Rapid Prototyping Journal 2018
79. Oh TS, Jeong WS, Chang TJ, Koh KS, Choi JW. Customized Orbital Wall Reconstruction Using Three-Dimensionally Printed Rapid Prototype Model in Patients With Orbital Wall Fracture. The Journal of craniofacial surgery 2016;27:2020-2024
80. Kang S, Kwon J, Ahn CJ, Esmaeli B, Kim GB, Kim N, Sa H-S. Generation of customized orbital implant templates using 3-dimensional printing for orbital wall reconstruction. Eye 2018;32:1864-1870 https://doi.org/10.1038/s41433-018-0193-1.
81. Raisian S, Fallahi HR, Khiabani KS, Heidarizadeh M, Azdoo S. Customized Titanium Mesh Based on the 3D Printed Model vs. Manual Intraoperative Bending of Titanium Mesh for Reconstructing of Orbital Bone Fracture: A Randomized Clinical Trial. Rev Recent Clin Trials 2017;12:154-158
82. Gerbino G, Zavattero E, Bosco G, Berrone S, Ramieri G. Temporomandibular joint reconstruction with stock and custom-made devices: Indications and results of a 14-year experience. Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery 2017;45:1710-1715
83. Ackland DC, Robinson D, Redhead M, Lee PVS, Moskaljuk A, Dimitroulis G. A personalized 3D-printed prosthetic joint replacement for the human temporomandibular joint: From implant design to implantation. Journal of the mechanical behavior of biomedical materials 2017;69:404-411

84. Dimitroulis G, Austin S, Sin Lee PV, Ackland D. A new three-dimensional, print-on-demand temporomandibular prosthetic total joint replacement system: Preliminary outcomes. J Cranio Maxill Surg 2018;46:1192-1198 http://www.sciencedirect.com/science/article/pii/S1010518218302658.
85. Mian M, Ackland D, Fink S, Wang N, Dimitroulis G. Accuracy of custom temporomandibular joint replacement surgery using a virtual surgical planning protocol. Oral Maxillofac Surg 2020
86. Adell R, Lekholm U, Rockler B, Brånemark PI. A 15-year study of osseointegrated implants in the treatment of the edentulous jaw. International Journal of Oral Surgery 1981;10:387-416 http://www.sciencedirect.com/science/article/pii/S0300978581800774.
87. Albrektsson T, Dahl E, Enbom L, Engevall S, Engquist B, Eriksson AR, Feldmann G, Freiberg N, Glantz PO, Kjellman O, et al. Osseointegrated oral implants. A Swedish multicenter study of 8139 consecutively inserted Nobelpharma implants. Journal of periodontology 1988;59:287-296
88. Buser D, Mericske-Stern R, Bernard JP, Behneke A, Behneke N, Hirt HP, Belser UC, Lang NP. Long-term evaluation of non-submerged ITI implants. Part 1: 8-year life table analysis of a prospective multi-center study with 2359 implants. Clinical oral implants research 1997;8:161-172
89. Lindquist LW, Carlsson GE, Jemt T. A prospective 15-year follow-up study of mandibular fixed prostheses supported by osseointegrated implants. Clinical results and marginal bone loss. Clinical oral implants research 1996;7:329-336
90. Chrcanovic BR, Albrektsson T, Wennerberg A. Bone Quality and Quantity and Dental Implant Failure: A Systematic Review and Meta-analysis. The International journal of prosthodontics 2017;30:219-237
91. Goiato MC, dos Santos DM, Santiago JF, Jr., Moreno A, Pellizzer EP. Longevity of dental implants in type IV bone: a systematic review. International journal of oral and maxillofacial surgery 2014;43:1108-1116
92. Mittal Y, Jindal G, Garg S. Bone manipulation procedures in dental implants. Indian J Dent 2016;7:86-94 https://pubmed.ncbi.nlm.nih.gov/27433052 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4934094/.
93. Gaviria L, Salcido JP, Guda T, Ong JL. Current trends in dental implants. J Korean Assoc Oral Maxillofac Surg 2014;40:50-60 https://pubmed.ncbi.nlm.nih.gov/24868501 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4028797/.

94. Cerea M, Dolcini G. Custom-Made Direct Metal Laser Sintering Titanium Subperiosteal Implants: A Retrospective Clinical Study on 70 Patients. BioMed Research International 2018;2018:1-11

95. Mangano C, Bianchi A, Mangano FG, Dana J, Colombo M, Solop I, Admakin O. Custom-made 3D printed subperiosteal titanium implants for the prosthetic restoration of the atrophic posterior mandible of elderly patients: a case series. 3D Printing in Medicine 2020;6:1 https://doi.org/10.1186/s41205-019-0055-x.

96. Ackland DC, Moskaljuk A, Hart C, Vee Sin Lee P, Dimitroulis G. Prosthesis loading after temporomandibular joint replacement surgery: a musculoskeletal modeling study. Journal of biomechanical engineering 2015;137:041001

97. Chen S, Pan Z, Wu Y, Gu Z, Li M, Liang Z, Zhu H, Yao Y, Shui W, Shen Z, Zhao J, Pan H. The role of three-dimensional printed models of skull in anatomy education: a randomized controlled trail. Scientific Reports 2017;7:575 https://doi.org/10.1038/s41598-017-00647-1.

98. Chan HHL, Siewerdsen JH, Vescan A, Daly MJ, Prisman E, Irish JC. 3D Rapid Prototyping for Otolaryngology-Head and Neck Surgery: Applications in Image-Guidance, Surgical Simulation and Patient-Specific Modeling. PLoS One 2015;10:e0136370-e0136370 https://www.ncbi.nlm.nih.gov/pubmed/26331717 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4557980/.

99. Lobb DC, Cottler P, Dart D, Black JS. The Use of Patient-Specific Three-Dimensional Printed Surgical Models Enhances Plastic Surgery Resident Education in Craniofacial Surgery. J Craniofac Surg 2019;30:339-341 <Go to ISI>://WOS:000467717400048.

100. Narayanan V, Narayanan P, Rajagopalan R, Karuppiah R, Rahman ZA, Wormald PJ, Van Hasselt CA, Waran V. Endoscopic skull base training using 3D printed models with pre-existing pathology. Eur Arch Otorhinolaryngol 2015;272:753-757

101. Nicot R, Druelle C, Schlund M, Roland-Billecart T, Gwenael R, Ferri J, Gosset D. Use of 3D printed models in student education of craniofacial traumas. Dent Traumatol 2019;35:296-299 <Go to ISI>://WOS:000473761500001.

102. Werz SM, Zeichner SJ, Berg BI, Zeilhofer HF, Thieringer F. 3D Printed Surgical Simulation Models as educational tool by maxillofacial surgeons. Eur J Dent Educ 2018;22:e500-e505

103. Zheng Y, Lu B, Zhang J, Wu G. CAD/CAM silicone simulator for teaching cheiloplasty: description of the technique. Br J Oral Maxillofac Surg 2015;53:194-196

104. Favier V, Zemiti N, Caravaca Mora O, Subsol G, Captier G, Lebrun R, Crampette L, Mondain M, Gilles B. Geometric and mechanical evaluation of 3D-printing materials for skull base anatomical education and endoscopic surgery simulation - A first step to create reliable customized simulators. PLoS One 2017;12:e0189486-e0189486 https://www.ncbi.nlm.nih.gov/pubmed/29252993 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5734742/.

105. Hochman JB, Rhodes C, Wong D, Kraut J, Pisa J, Unger B. Comparison of cadaveric and isomorphic three-dimensional printed models in temporal bone education. Laryngoscope 2015;125:2353-2357

106. Okumoto T, Sakamoto Y, Kondo S, Ogata H, Kishi K, Yoshimura Y. Salt as a new colored solid model for simulation surgery. The Journal of craniofacial surgery 2015;26:680-681

107. Unger BJ, Kraut J, Rhodes C, Hochman J. Design and Validation of 3D Printed Complex Bone Models with Internal Anatomic Fidelity for Surgical Training and Rehearsal. Stud Health Technol Inform 2014;196:439-445

108. Hacioglu A, Yılmazer H, Ustundag C. 3D Printing for Tissue Engineering Applications. Journal of Polytechnic 2018

109. Starly B, Shirwaiker R. Chapter 3 - 3D Bioprinting Techniques. In: Zhang LG, Fisher JP, Leong KW, eds. 3D Bioprinting and Nanotechnology in Tissue Engineering and Regenerative Medicine: Academic Press, 2015:57-77.

110. Tamay DG, Dursun Usal T, Alagoz AS, Yucel D, Hasirci N, Hasirci V. 3D and 4D Printing of Polymers for Tissue Engineering Applications. Frontiers in Bioengineering and Biotechnology 2019;7https://www.frontiersin.org/article/10.3389/fbioe.2019.00164.

111. Tao O, Kort-Mascort J, Lin Y, Pham HM, Charbonneau AM, ElKashty OA, Kinsella JM, Tran SD. The Applications of 3D Printing for Craniofacial Tissue Engineering. Micromachines 2019;10

112. Murphy S, Atala A. 3D Bioprinting of Tissues and Organs. Nature biotechnology 2014;32

113. Adamzyk C, Kachel P, Hoss M, Gremse F, Modabber A, Hölzle F, Tolba R, Neuss S, Lethaus B. Bone tissue engineering using polyetherketoneketone scaffolds combined with autologous mesenchymal stem cells in a sheep calvarial defect model. Journal of Cranio-Maxillofacial Surgery 2016;44:985-994 http://www.sciencedirect.com/science/article/pii/S101051821630021X.

114. Kwon DY, Park JH, Jang SH, Park JY, Jang JW, Min BH, Kim W-D, Lee HB, Lee J, Kim MS. Bone regeneration by means of a three-dimensional printed scaffold in a rat cranial defect. Journal of Tissue Engineering and Regenerative Medicine 2018;12:516-528 https://onlinelibrary.wiley.com/doi/abs/10.1002/term.2532.

115. Li J, Xu Q, Teng B, Yu C, Li J, Song L, Lai Y-x, Zhang J, Zheng W, Ren P-G. Investigation of angiogenesis in bioactive 3-dimensional poly(d,l-lactide-co-glycolide)/nano-hydroxyapatite scaffolds by in vivo multiphoton microscopy in murine calvarial critical bone defect. Acta Biomaterialia 2016;42:389-399 http://www.sciencedirect.com/science/article/pii/S1742706116303014.

116. Smeets R, Barbeck M, Hanken H, Fischer H, Lindner M, Heiland M, Wöltje M, Ghanaati S, Kolk A. Selective laser-melted fully biodegradable scaffold composed of poly(d,l-lactide) and β-tricalcium phosphate with potential as a biodegradable implant for complex maxillofacial reconstruction: In vitro and in vivo results. Journal of Biomedical Materials Research Part B: Applied Biomaterials 2017;105:1216-1231 https://onlinelibrary.wiley.com/doi/abs/10.1002/jbm.b.33660.

117. Keriquel V, Oliveira H, Rémy M, Ziane S, Delmond S, Rousseau B, Rey S, Catros S, Amédée J, Guillemot F, Fricain J-C. In situ printing of mesenchymal stromal cells, by laser-assisted bioprinting, for in vivo bone regeneration applications. Scientific Reports 2017;7:1778 https://doi.org/10.1038/s41598-017-01914-x.

118. Albanna M, Binder KW, Murphy SV, Kim J, Qasem SA, Zhao W, Tan J, El-Amin IB, Dice DD, Marco J, Green J, Xu T, Skardal A, Holmes JH, Jackson JD, Atala A, Yoo JJ. In Situ Bioprinting of Autologous Skin Cells Accelerates Wound Healing of Extensive Excisional Full-Thickness Wounds. Scientific Reports 2019;9:1856 https://doi.org/10.1038/s41598-018-38366-w.

119. Cubo N, Garcia M, del Cañizo JF, Velasco D, Jorcano JL. 3D bioprinting of functional human skin: production and in vivo analysis. Biofabrication 2016;9:015006 http://dx.doi.org/10.1088/1758-5090/9/1/015006.

120. He P, Zhao J, Zhang J, Li B, Gou Z, Gou M, Li X. Bioprinting of skin constructs for wound healing. Burns Trauma 2018;6:5-5 https://pubmed.ncbi.nlm.nih.gov/29404374 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5778803/.

121. Michael S, Sorg H, Peck C-T, Koch L, Deiwick A, Chichkov B, Vogt PM, Reimers K. Tissue engineered skin substitutes created by laser-assisted bioprinting form skin-like structures in the dorsal skin fold chamber in mice. PLoS One 2013;8:e57741-e57741 https://pubmed.ncbi.nlm.nih.gov/23469227

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3587634/.
122. Seol Y-J, Lee H, Copus JS, Kang H-W, Cho D-W, Atala A, Lee SJ, Yoo JJ. 3D bioprinted biomask for facial skin reconstruction. Bioprinting 2018;10:e00028 http://www.sciencedirect.com/science/article/pii/S2405886618300137.
123. Kundu J, Shim J-H, Jang J, Kim S-W, Cho D-W. An additive manufacturing-based PCL–alginate–chondrocyte bioprinted scaffold for cartilage tissue engineering. Journal of Tissue Engineering and Regenerative Medicine 2015;9:1286-1297 https://doi.org/10.1002/term.1682.
124. Lee J-S, Hong JM, Jung JW, Shim J-H, Oh J-H, Cho D-W. 3D printing of composite tissue with complex shape applied to ear regeneration. Biofabrication 2014;6:024103 http://dx.doi.org/10.1088/1758-5082/6/2/024103.
125. Markstedt K, Mantas A, Tournier I, Martínez Ávila H, Hägg D, Gatenholm P. 3D Bioprinting Human Chondrocytes with Nanocellulose–Alginate Bioink for Cartilage Tissue Engineering Applications. Biomacromolecules 2015;16:1489-1496 https://doi.org/10.1021/acs.biomac.5b00188.
126. Ujam A, Gardner O, Gomez EC, Agabalyan N, Bulstrode N, Ferretti P. 3D Bioprinting cartilage for facial reconstruction. British Journal of Oral and Maxillofacial Surgery 2019;57:e88-e89 https://doi.org/10.1016/j.bjoms.2019.10.258.
127. Garcia J, Yang Z, Mongrain R, Leask RL, Lachapelle K. 3D printing materials and their use in medical education: a review of current technology and trends for the future. BMJ Simul Technol Enhanc Learn 2018;4:27-40 https://pubmed.ncbi.nlm.nih.gov/29354281 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5765850/.
128. Gross BC, Erkal JL, Lockwood SY, Chen C, Spence DM. Evaluation of 3D Printing and Its Potential Impact on Biotechnology and the Chemical Sciences. Analytical Chemistry 2014;86:3240-3253 https://doi.org/10.1021/ac403397r.

Figure Captions

Figure 1: Typical workflow for the production of a 3D printed medical device in oral and maxillofacial surgery

Figure 2: Main 3D printing techniques including (A) fused deposition modelling, (B) powered bed fusion, (C) stereolithography and (D) material jetting.

Figure 3: A composite 3D printed mandible showing the inferior alveolar nerve (colourised).

Figure 4: Surgical cutting guides for mandibular reconstruction showing (A) preoperative mandible model with a large right sided ameloblastoma (colourised), (B) preoperative fibula with 3D printed cutting guide in place and (C) planned postoperative mandibular reconstruction.

Figure 5: 3D printed titanium plates for bimaxillary advancement on a 3D printed model.

Figure 6: Personalised 3D printed titanium implant for orbital floor reconstruction following blowout fracture.

Figure 7: Personalised 3D printed TMJ implant showing (A) preoperative STL reconstruction and (B) postoperative radiograph.

Figure 8: Subperiosteal implant for prosthetic rehabilitation of an atrophic maxilla showing (A) implant and prosthesis on a 3D printed model and (B) post-operative radiograph.

Figure 1

CT or MRI scan of relevant anatomy

↓

Image saved in DICOM format

↓

Image processing: segmentation and 3D reconstruction

↓

Saved in STL format

↓

Computer-aided design of planned object

↓

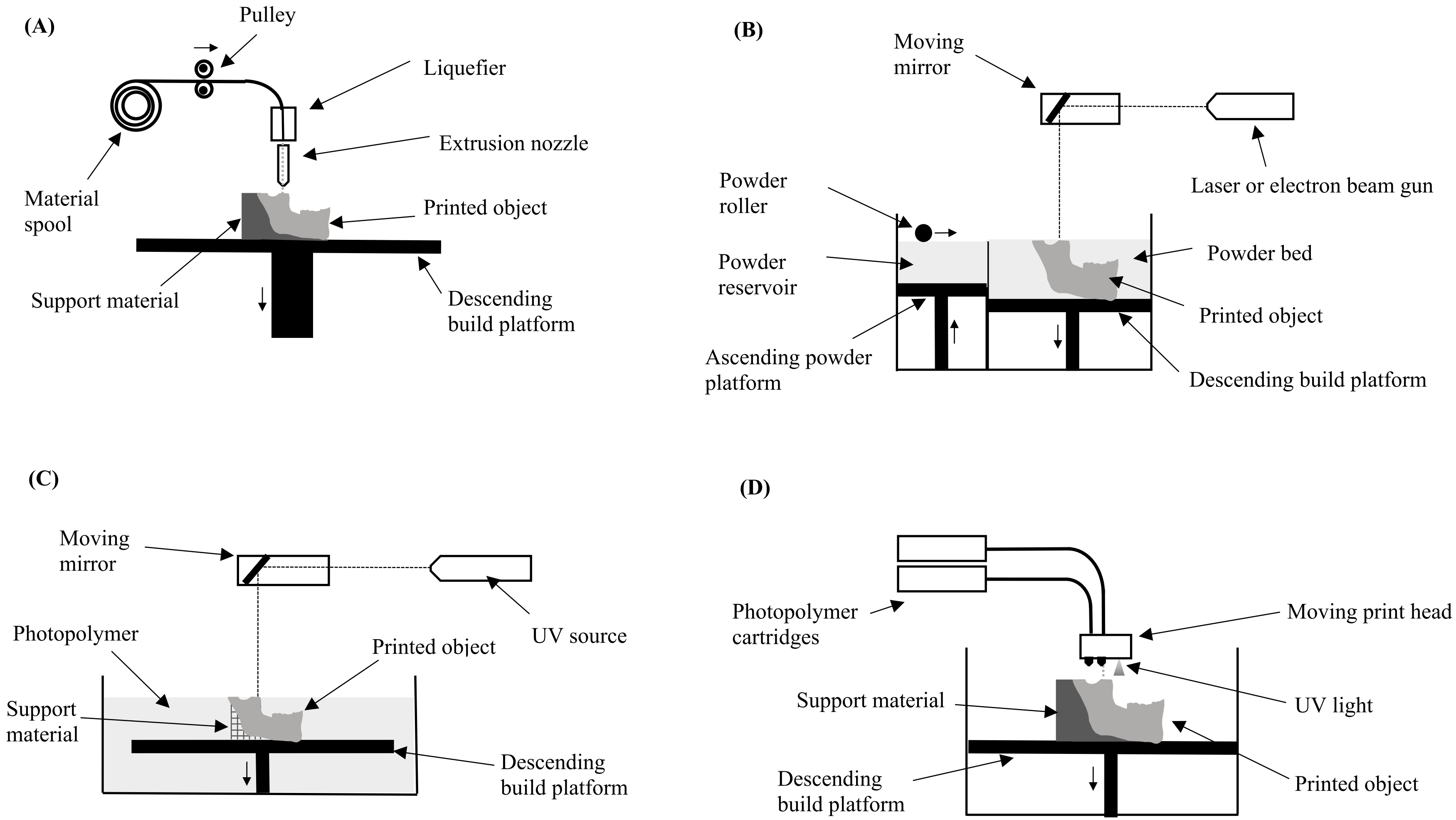
G-code directs the 3D printer

↓

3D printing: specific technique depending on application and material to be used

↓

Figure 2



(A)
Pulley
Liquefier
Extrusion nozzle
Material spool
Printed object
Support material
Descending build platform
(B)
Moving mirror
Laser or electron beam gun
Powder roller
Powder reservoir
Powder bed
Printed object
Ascending powder platform
Descending build platform
(C)
Moving mirror
UV source
Photopolymer
Printed object
Support material
Descending build platform
(D)
Photopolymer cartridges
Moving print head
Support material
UV light
Descending build platform
Printed object

Figure 3

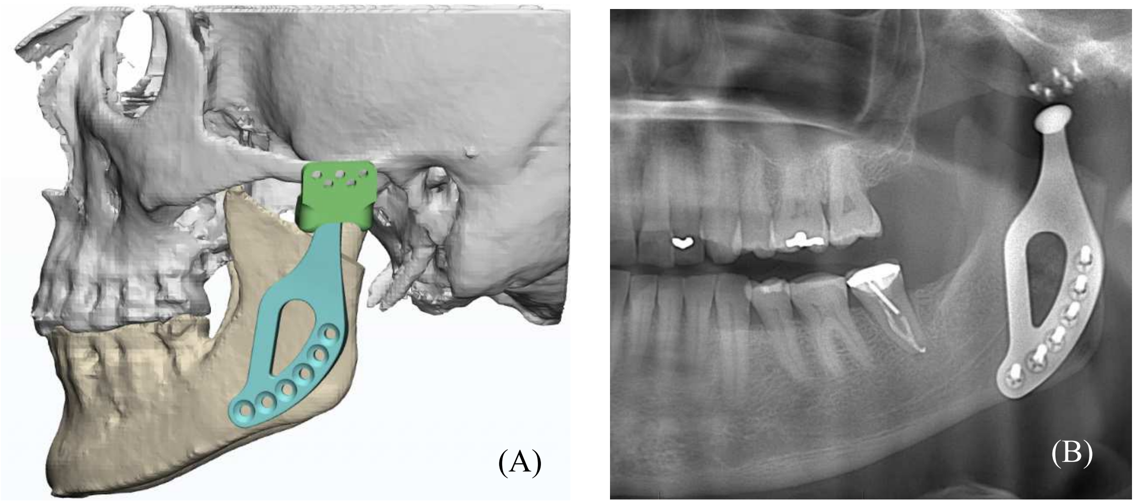
(A) (B) (C)

Figure 4

Figure 5

Figure 6

Figure 7



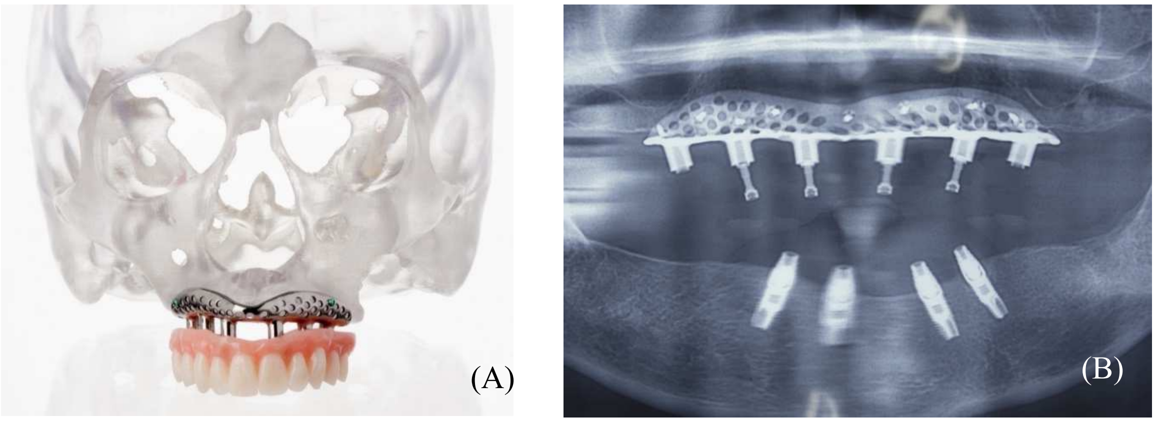


Figure 8

Table 1

Materials available for each 3D printing technique

	Polymers	Metals		Ceramics
		Pure	Alloys	
Fused deposition modelling (FDM*)*	◆			
Powder bed fusion processes				
Selective laser sintering	◆	◆	◆	◆
Selective laser melting		◆		
Electron beam melting		◆		
Stereolithography	◆			
Inkjet processes				
Binder jetting	◆		◆	◆