Review

New frontiers and emerging applications of 3D printing in ENT surgery: a systematic review of the literature

Nuove frontiere e applicazioni emergenti della stampa 3D in ORL: revisione sistematica della letteratura

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SUMMARY

3D printing systems have revolutionised prototyping in the industrial field by lowering production time from days to hours and costs from thousands to just a few dollars. Today, 3D printers are no more confined to prototyping, but are increasingly employed in medical disciplines with fascinating results, even in many aspects of otorhinolaryngology. All publications on ENT surgery, sourced through updated electronic databases (PubMed, MEDLINE, EMBASE) and published up to March 2017, were examined according to PRISMA guidelines. Overall, 121 studies fulfilled specific inclusion criteria and were included in our systematic review. Studies were classified according to the specific field of application (otologic, rhinologic, head and neck) and area of interest (surgical and preclinical education, customised surgical planning, tissue engineering and implantable prosthesis). Technological aspects, clinical implications and limits of 3D printing processes are discussed focusing on current benefits and future perspectives.

KEY WORDS: 3D printing • Additive manufacturing • Rapid prototyping • Otorhinolaryngology • ENT • Systematic review

Introduction

Around 1450, Gutenberg developed a printing system that became a stepping-stone in the timeline of communication technology, and considered as one of the most influential events in the sharing of scientific and medical knowledge. Since its first introduction in the early 1980s, 3D printing (3DP) technology has rapidly caught the interest of the industry, healthcare and media with an overall business of $700 million\textsuperscript{1, 4}. The nature of all 3D printers is the creation of a wide range of 3D objects obtained from digital data of easy management and available in open-access digital databas-
3D printing in ENT surgery

es, allowing a unique opportunity for information exchange (e.g. 3dprint.nih.gov). Almost anything can be produced by 3DP systems: fuel injectors for rockets, jewels and hearing aid shells \(^5\). One of the most fascinating aspects of this technology concerns the employment of imaging studies. Today, radiology plays a pivotal role in diagnostic and therapeutic decision making. However, scans are still displayed on flat screens, resulting in a 2D representation of reality. Surgeons’ experience the difficult task of figuring out a three-dimensional image on a daily basis, by analysing CT or MRI-slices in separate two-dimensional axial, coronal and sagittal projections \(^7\). 3DP systems allow to restore the third dimension that is lacking during visualisation of radiological image data. Along with the production of anatomical models addressed to customised surgical planning, medical teaching and surgical training, research in 3DP has explored the pioneering world of biologic tissue engineering, patient-specific implantation and ultimately of personalised pharmacoprinting. The increasing impact of 3DP processes in the scientific literature has recently involved many aspects of otorhinolaryngology, often followed by great expectations regarding patient care. Up to now, what are the applications of 3DP technologies in ENT surgery? Does this tool provide any substantial benefits in the ENT field? And what about future perspectives? The present work aims to answer these questions by carrying out a systematic review of the literature on the topic, a task that, to the best of our knowledge, has not undertaken previously.

The technology of 3DP systems

3DP is a subset of additive manufacturing (AM) or rapid prototyping in which objects are achieved by gradually layering material, rather than by subtraction from the raw material as is in the case of conventional technologies \(^8\). The main advantages of AM are its flexibility, precision and relative quickness in creating customised physical structures of almost any complex shape in a myriad of materials. Historically, 3DP processes were employed by the manufacturing industry to rapidly produce a representation of a system or a part before final release or commercialisation \(^9\). The 3DP was first conceived by C. Hull in 1986 as an “apparatus for production of three-dimensional objects by stereolithography” \(^3\). During the same year, he also developed the “Standard Triangulation Language” (.STL) file format, which makes it possible to deconstruct the surface of a three-dimensional object in a series of triangles. The .STL file can be obtained from a 3D “Computer-Aided Design” (CAD) software, a medical scan data (e.g. CT scan, MRI), or from existing objects by using point or laser scanners. This virtual model is subsequently sliced into thin 2D layers, which are then sent to the 3D printer. 3DP methodologies differ from one another in the way that materials are deployed and cured \(^8\). Recently, the ASTM International Committee F42 classified 3DP technologies in 7 different working process categories \(^10\) (Fig. 1).

I. Vat photopolymerisation: in this technique a container gets filled with photopolymeric resin. This resin is then hardened by an UV light source.

II. Material jetting: this process resembles inkjet paper printing, since the material is dropped through small diameter nozzles. In this case, the base material is a photopolymeric resin subsequently hardened by a UV lamp.

III. Binder jetting: this method employs a powder base material and a liquid binder. In the build chamber, the powder is spread in equal layers and binder is applied through jet nozzles that “glue” the powder particles together in the shape of a programmed 3D object.

IV. Material extrusion: the most widespread and popular 3DP technology on the market. These printers are fed a thermo-plastic filament that gets pushed through a heating chamber: the fused material is moulded and then solidified through cooling, allowing the deposition of successive layers.

V. Powder bed fusion: this technology uses a high-power laser source to fuse small particles of plastic, metal, ceramic or glass powders into a mass that has the desired three-dimensional shape. The laser selectively fuses the powdered material by scanning the cross-sections generated by the 3D modelling program on the surface of a powder bed.

VI. Sheet lamination: in this technique sheets of material are bound together through external force. These processes can be further categorised based on the mechanism employed to achieve bonding between layers: gluing or adhesive bonding, thermal bonding, clamping, or ultrasonic welding.

VII. Direct energy deposition: this process, mostly used in the high-tech metal industry, enables the creation of parts by melting material as it is being deposited. The 3DP is usually attached to a multi-axis robotic arm composed of a nozzle that deposits metal powder or wire on a surface and an energy source (laser, electron beam or plasma arc) that melts it, forming a solid object.

Materials and methods

All existing articles sourced through updated electronic databases (PubMed, MEDLINE, EMBASE) and published up to March 2017 were examined according to the “Preferred Reporting Items for Systematic Reviews and Meta-analyses” (PRISMA) guidelines \(^11\). The research was conducted using the following keywords: “3D printing OR three di-
Fig. 1. Schematic representation of AM technologies: (A) vat photopolymerisation, (B) material jetting, (C1, C2) binder jetting (R: resin, SM: supporting material, UV: UV lamp), (D) material extrusion, (E1, E2) powder bed fusion, (F) sheet lamination, (G) direct energy deposition.
dimensional printing AND otorhinolaryngology NOT plastic surgery”, “3D printing OR three dimensional printing AND ENT NOT plastic surgery”, “3D printing OR three dimensional printing AND otology NOT plastic surgery”, “3D printing OR three dimensional printing AND rhinology NOT plastic surgery”, “3D printing OR three dimensional printing AND head neck NOT plastic surgery”, “3D Printing OR three-dimensional printing AND mandible NOT plastic surgery”. Other sources analysed for additional relevant trials were reference lists of previous systematic reviews and evaluated works, journal homepages and publications citing included trials. Furthermore, experts in the field of 3D printing and engineering were contacted to ensure that all relevant studies had been included. Searches were done at all stages, from the initial drafting of the paper to submission of the revised and final version. Works lacking clinical or surgical relevance, such as engineering and bio-engineering publications and those regarding the evaluation of accuracy of the 3DP models were excluded since these are out of the expertise of ENT surgeons. Moreover, papers primarily addressing maxillofacial surgery, plastic surgery, thoracic surgery, neurosurgery and dentistry were also excluded. Exclusion criteria also applied to animal research and studies with ambiguous information regarding the modalities of production and employment of the 3DP methodology. Articles not written in English, review articles, letters, editorials and congress abstracts were omitted as well. All the considered studies were classified according to the specific field of application (otologic, rhinologic, head and neck). Each field was furthermore categorised into three distinct areas of interest: surgical and preclinical education, customised surgical planning and tissue engineering and implantable prostheses.

Results

The electronic database search yielded 258 citations and a further 123 articles were identified from additional sources, but after removing duplicates the total number of articles decreased to 278. A total of 157 records were removed as they did not fulfil inclusion criteria. Overall, 121 studies were included in the systematic review (Fig. 2). Figure 3 shows the studies according to the spe-
cific field of application (otologic, rhinologic, head and neck) and area of interest (surgical and preclinical education, customised surgical planning, tissue engineering and implantable prostheses). The total number of articles in Figure 3 is 135, and not 121, since 14 articles belong to more than one field of application and/or area of interest. Employed AM technology is summarised in Figure 4 considering the three areas of interest.

**Otologic applications (Table I)**

**Surgical and preclinical education**

- Twenty-three studies of the otologic ones (n = 39) involved the surgical and preclinical education area (59.0%) and mostly concerned the field of temporal bone dissection. Since the first report in 1998, technological efforts aimed to overcome the restrictions of the initial 3DP models. These first models, which employed a sole material and a single colour, allowed acceptable anatomical results, but limited haptic and drilling features. The evolution of 3DP systems (e.g. binder jetting) led to greater anatomical fidelity thanks to the employment of multiple colours and materials that are able to reproduce the mechanical properties of trabecular mastoid bone with realistic drilling experience. Moreover, the development of printed models coupled with electronic simulators provided a real-time alert in case of injury to vital structures during dissecting practice.

**Customised surgical planning**

- The production of patient-specific 3DP temporal bones based on preoperative CT was considered suitable for surgical planning and simulation in five cases of challenging anatomy (e.g. congenital aural atresia, acquired subverted anatomy) and in one case of cochlear implant surgery. Four papers dealt with the creation of 3DP operative templates to assist surgical positioning of a transcutaneous bone-conduction hearing device. Finally, six studies were on the combined use of surgical navigation and 3DP technology. In particular, a Japanese publication described the development of a registration method based on bone-anchored fiducial markers using 3DP templates without requiring a preoperative invasive marking process or additional CT. Since its first publication, this process has been simplified and further improved.

**Tissue engineering and implantable prosthetics**

- Kozin et al. tested a customised 3DP prosthesis for repair of bony superior canal defects on cadaveric temporal bones, even if clinical uses were not yet reported.

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Fig. 3. Number of studies according to ENT field.
Table I. Otologic studies classified according to each area of interest.

| Field of work                        | Authors, year | AM category | 3D printer | 3DPMaterial |
|--------------------------------------|---------------|-------------|------------|-------------|
| Surgical and preclinical education   |               |            |            |             |
| Temporal bone dissection training model | Cohen J et al., 2015 | Material extrusion | Dimensions SST 1200es | Abs + resin (support material) |
|                                      | Da Cruz MJ et al., 2015 | Binder jetting | Spectrum Z510 | Chalk-like powder + binder + colors |
|                                      | Hochman JB et al., 2015 (1) | Binder jetting | ZPrinter 650 | Chalk-like powder + binder + colors |
|                                      | Hochman JB et al., 2015 (2) | Binder jetting | ZPrinter 650 | Chalk-like powder + binder + colors |
|                                      | Longfield EA et al., 2015 | Binder jetting | Spectrum Z510 | Chalk-like powder + binder + colors |
|                                      | Mowry SE et al., 2015 | Material extrusion | MakerBot 2x | ABS + HIPS |
|                                      | Rose AS et al., 2015 | Vat photopolymerisation | Objet Connex 350 | Photo-polymer resins with different mechanical properties |
|                                      | Hochman JB et al., 2014 | Binder jetting | ZPrinter 650 | Chalk-like powder + binder + colors |
|                                      | Unger BJ et al., 2014 | Binder jetting | ZPrinter 650 | Chalk-like powder + binder + colors |
|                                      | Mick PT et al., 2013 | Binder jetting | ZPrinter 650 | Zp®131 powder binder(Zb®7) + colors |
|                                      | Roossi C et al., 2013 | Binder jetting | Spectrum Z510 | Chalk-like powder + binder + colors |
|                                      | Bakhos D et al., 2010 | Vat photopolymerisation | SLA®5000 | Somos® 14120 |
|                                      | Mori K, 2009 | Powder bed fusion | NA | Polyamide nylon and glass beads |
|                                      | Mori K et al., 2009 | Powder bed fusion | NA | Polyamide nylon and glass beads |
|                                      | Mori K et al., 2008 | Powder bed fusion | NA | Polyamide nylon and glass beads |
|                                      | Suzuki M et al., 2007 | Powder bed fusion | NA | Polyamide nylon and glass beads |
|                                      | Grunert S et al., 2006 | Binder jetting | Spectrum Z510 | Plaster + post-processing with polyurethane and acetone |
|                                      | Suzuki M et al., 2004 (1) | Powder bed fusion | NA | Polyamide nylon and glass beads |
|                                      | Suzuki M et al., 2004 (2) | Powder bed fusion | NA | Polyamide nylon and glass beads |
|                                      | Begall K et al., 1998 | Vat photopolymerisation | Laser Model stereolithographic System by Fockele & Schwarze GmbH | Photosensitive; exopy resins |

Fig. 4. Employed AM technology considering the area of interest.

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Rhinologic applications (Table II)

Surgical and preclinical education 51-57
Four studies focused on the development of 3DP training models for endoscopic sinonasal and skull base surgery 51-54. Medium-high fidelity simulators allowed developing surgical skills in the main endoscopic procedures, including drilling techniques and skull base exposure. Low-cost models were primary limited by the materials employed to mimic human bone as much as possible.

Customised surgical planning 58-60
Two studies took advantage of the versatility of 3DP systems to fabricate operative templates tailored on the patient’s anatomy. Daniel et al. produced 3DP cutting guides to design an osteoplastic flap during frontal surgery 59; Onerci Altunay et al. used 3DP templates to fashion septal prosthesis for large irregular septal perforations 58. 3DP endoscopic sinus surgery simulation was carried out in two patients with chronic rhinosinusitis to obtain safer and faster procedures 60.
One child with a craniofacial fibrous dysplasia was submitted to resection and reconstruction of the fronto-orbital region by means of a custom 3DP polyetheretherketone implant resulting in good aesthetical and safe outcomes.

Head and neck applications (Table III)

Two studies focused on resident training for laryngeal surgical procedures. In 2014, Ainsworth et al. created a laryngeal model, including the extra-laryngeal soft tissues, to simulate trans-cervical injection of vocal folds. More recently, Kavanagh et al. developed a 3DP paediatric laryngeal model reproducing several challenging surgical conditions (e.g. subglottic cysts, laryngomalacia, subglottic stenosis and laryngeal clefts).

Customised surgical planning

This was the most frequent ENT application of 3DP technology and mentioned in 68 of the 121 papers (56.2%). Among these, 95.6% of studies (65 out of 68) concerned surgical management of head and neck tumours requiring mandibular resection and/or reconstruction. The first date to the ’90s and dealt with creation of 3DP mandibles to allow a direct handling of the neoplastic lesion, leading to the early surgical resection simulators. However, the most relevant contribution concerned the reconstructive aspects of oncologic surgery, guiding the employment of plates or autografts. Patient-specific 3DP mandibles were developed to “pre-bent” plates preoperatively. More recently, the introduction of image-guide systems used to plan the harvest and positioning of autografts (e.g. fibula flap, iliac crest bone flap) has led to the production of self-fabricated customised mandibles.
### Table III. Head and neck studies classified according to each area of interest.

| Field of work | Authors, year | AM category | 3D printer | 3DP material |
|---------------|---------------|-------------|------------|--------------|
| **SURGICAL AND PRECLINICAL EDUCATION** | | | | |
| Laryngeal model | Kavanagh KR et al., 2017 62 | Material extrusion | MakerBot | ABS, PLA, HIPS |
| | Johnson CM et al., 2016 63 | Material extrusion | MakerBot 2XL | ABS (best performance), HIPS, PLA; Dragon Skin Fast silicon casting in a 3D printed mold |
| | Ainsworth TA et al., 2014 64 | Material extrusion | Dimension Elite - Stratasys | ABSplus + silicone casting |
| Carotid artery model | Govsa F et al., 2017 65 | Material extrusion | MakerBot | PLA |
| Tracheostoma model | Grolman W et al., 1995 66 | Vat photopolimerisation | NA | Synthetic liquid resin |
| **CUSTOMISED SURGICAL PLANNING** | | | | |
| Guided surgery for oromandibular resection and reconstruction | Bosc R et al., 2017 67 | Material jetting | Objet 30Pro – Stratasys Zortrax M200 - Zortrax SARL | Biocompatible photopolymer ABS |
| | Rachmiel A et al., 2017 68 | Material extrusion | Objet260 Dental - Stratasys | Photopolimer resin |
| | | Powder bed fusion | EOS | Titanium |
| | | Binder jetting | ZPrinter 310 plus | Gypsum-based material |
| | Shah S et al., 2017 69 | Powder bed fusion | Arcam A1 (Electron Beam Melting) | Ti-6Al-4 V-ELI medical grade powder |
| | Lee UL et al., 2016 70 | | | |
| | Lim SH et al., 2016 71 | Binder jetting | ProJet 360 - 3D Systems | NA |
| | | Material jetting | ProJet 3500 HDMax - 3D Systems | Biocompatible materials |
| | Numajiri T et al., 2016 72 | Material extrusion | MakerBot | PLA |
| | Yamada H et al., 2016 73 | NA | NA | NA |
| | Chan HHL et al., 2015 54 | Material extrusion | Vantage - Stratasys | ABS |
| | | Binder jetting | ZPrinter 310 - ZCorp | ZP-130 plaster powder + CA101 cyanoacrylate; ZP-15 plaster powder + infiltrant elastomeric |
| | | Material extrusion | Vantage - Stratasys | Polycarbonate |
| | Man QW et al., 2015 74 | NA | NA | NA |
| | Modabber A et al., 2015 75 | Powder bed fusion | NA | Polyamide Powder |
| | Reiser V et al., 2015 76 | Material jetting | A Objet – Stratasys machine (Model NA) | Biocompatible plastic polymers |
| | Schepers RH et al., 2015 77 | NA | NA | Polyamide (for the cutting guides) |
| | Shan XF et al., 2015 78 | Material extrusion | Stratasys FDM 400-mc | NA |
| | | Residual skull | Mesh | Titanium |
| | Steinbacher DM et al., 2015 79 | NA | NA | NA |
| | Succo G et al., 2015 80 | Powder bed fusion | NA | Polyamide |
| | Wilde F et al., 2015 81 | Powder bed fusion | NA | NA |
| | Ayoub N et al., 2014 82 | Binder jetting | ZPrinter 310 plus | NA |
| | Azuma M et al., 2014 83 | | | |

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### CUSTOMISED SURGICAL PLANNING

| Field of work | Authors, year | AM category | 3D printer | 3DP material |
|---------------|---------------|-------------|------------|--------------|
| de Farias TP et al., 2014 | Binder jetting | Z-Corp Spectrum Z510 | Gypsum, cyanoacrylate, and ZP150 |
| Liu YF et al., 2014 | Powder bed fusion | Sinterstation HiQ + HiSTM - 3D Systems | DuraForm - biocompatible nylon |
| Modabber A et al., 2014 | Powder bed fusion | NA | Polyamide |
| Tsai MJ et al., 2014 | NA | NA | NA |
| Watson J et al., 2014 | Powder bed fusion | Direct metal Powder bed fusion (Model NA) | Medical-grade titanium alloy Ti6Al4V - 3TRPD |
| Wilde F et al., 2014 | Powder bed fusion | NA | Biocompatible Polyamide |
| Yamada H et al., 2014 | NA | NA | NA |
| Coppen C et al., 2013 | Powder bed fusion | NA | DuraForm PA - 3DWorknet |
| Foley BD et al., 2013 | NA | NA | NA |
| Hansano MM et al., 2013 | Powder bed fusion | NA | Biocompatible Polyamide |
| Mazzoni S et al., 2013 | Powder bed fusion | EOSINT M270 - Electro-Optical Systems | EOS Titanium Ti64 |
| | Guide | EOSINT M270 - Electro-Optical Systems | EOS Cobalt-Chrome MP1 |
| Mandible | Material extrusion | Stratasys machine | Resin |
| Zheng GS et al., 2013 | Vat photopolymerisation | SLA-3500 3D Systems | NA |
| Ciocca L et al., 2012 | Powder bed fusion | EOSINT M270 - Electro-Optical Systems | EOS Titanium Ti64 |
| | Guide | EOSINT M270 - Electro-Optical Systems | EOS Cobalt-Chrome MP1 |
| Mandible | Material extrusion | Stratasys machine | ABS |
| Ciocca L et al., 2012 | Powder bed fusion | EOSINT M270 - Electro-Optical Systems | EOS Titanium Ti64 |
| | Guide | EOSINT M270 - Electro-Optical Systems | EOS Cobalt-Chrome MP1 |
| Mandible | Material extrusion | Stratasys machine | ABS |
| Dérand P et al., 2012 | Powder bed fusion | ARCAM EBM A2 | Ti6Al4V ELI powder |
| Hou JS et al., 2012 | NA | NA | Photopolymer |
| Lethaus B et al., 2012 | Material extrusion | Maastricht Instruments | NA |
| Modabber A et al., 2012 | Powder bed fusion | NA | Polyamide |
| | Guide | NA | Acrylic Resin |
| Modabber A et al., 2012 | Powder bed fusion | NA | Polyamide |
| Skull | NA | NA | NA |
| Patel A et al., 2012 | NA | NA | NA |
| Sink J et al., 2012 | NA | NA | NA |
| Wilde F et al., 2012 | Binder jetting | ZTM 510 - 4D Concepts | NA |
| Zheng GS et al., 2012 | Vat photopolymerisation | SLA-3500 3D Systems | NA |
| Abou-ElFetouh A et al., 2011 | Vat photopolymerisation | 3D Systems InVision Si2 | NA |
| | Binder jetting | 3D Systems VisiJet SR 200 | NA |
| Antony AK et al., 2011 | NA | NA | Acrylic resin |
| Bell RB et al., 2011 | NA | NA | Polybutadiene-styrene resin |
| Hou JS et al., 2011 | NA | NA | Acrylic, Epoxy |
| Mehra Pet al., 2011 | Vat photopolymerisation | Material extrusion | Starch |

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### CUSTOMISED SURGICAL PLANNING

| Field of work                                      | Authors, year | AM category | 3D printer | 3DP material                     |
|----------------------------------------------------|---------------|-------------|------------|----------------------------------|
| Guided surgery for cranio-cervicofacial teratoma  | Wiedermann JP et al., 2017 | NA | NA | NA |

| Carotid artery model                               | Govsa F et al., 2017 | Material extrusion | MakerBot | PLA |

| MRI compatible laryngoscope                         | Paydarfar JA et al., 2016 | Material jetting | Objet Eden250 - Stratasys | MED610 (Stratasys) biocompatible photopolymer |

### TISSUE ENGINEERING AND IMPLANTABLE PROSTHESIS

| Field of work                                      | Authors, year | AM category | 3D printer | 3DP material |
|----------------------------------------------------|---------------|-------------|------------|--------------|
| Customised prosthesis for mandibular reconstruction| Rachmiel A et al., 2017 | Skull | Material jetting | Objet260 Dental - Stratasys | Photopolymer resin |
| Template                                           | Lee UL et al., 2016 | Powder bed fusion | EOS | Titanium |
| Powder bed fusion                                  | Schepers RH et al., 2015 | NA | NA | Polyamide (for the cutting guides) |
| Residual Skull                                     | Shan XF et al., 2015 | Material extrusion | Stratasys FDM 400-mc | NA |
| Mesh                                               | Watson J et al., 2014 | Powder bed fusion | Direct metal Powder bed fusion (Model NA) | Medical-grade titanium alloy Ti6AL4V - 3TRPD |
| Plate                                              | Mazzoni S et al., 2013 | Powder bed fusion | EOSINT M270 - Electro-Optical Systems | EOS Titanium Ti64 |
| Guide                                              | Mandible      | Powder bed fusion | EOSINT M270 - Electro-Optical Systems | Eos Cobalt-Chrome MP1 |

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customised 3DP cutting guides. Many authors experienced a decrease in surgical time and the risk of undesirable events during reconstructive approaches, which resulted in a proper mandibular function. Concerning AM technology, in 38.2% of the studies (26 of 68) the AM category was not specified, mainly due to the outsourcing of all 3D printing operations to external services, which are becoming more common in recent years.

**Discussion**

Personalised medicine, minimally-invasive surgery, tissue engineering and regenerative medicine are the watchwords of third millennium healthcare. The arising popularity around the world of 3DP systems may be explained through the opportunities offered by this new technology to support new trends in modern medicine. Since its first applications in the early 1990s, researchers have explored the advantages of 3D printers, publishing 121 studies in otorhinolaryngology (Fig. 2). Customised surgical planning was evaluated in 71.9% of studies, proving to be the main direction of investigation (Fig. 3). The development of 3DP operative templates for cutting and/or reconstruction guides minimised the surgeon’s fatigue and complication rates, and optimised the operating room time, which led to lower morbidity. Similar approaches have been employed for complex cases of temporal bone and sinonasal surgery.

Clinical benefits were advocated by the authors to justify the main limitations of AM technology: costs, necessity for technical skills and technological availability. Cost-effectiveness was widely debated in literature: the decreased surgical time and employment of self-fabricated 3DP models or guides (instead of outsourced manufacturing) appeared to counter balance the price of the starting technological investments and the technical skills required.
for pre- and postprocessing printing activity. Interestingly, for 34% of studies on customised surgical planning, a specific description of the technology adopted was not available (Fig. 4): this arises from the choice of externalisation of the 3D printing process, as often declared by authors themselves. To date, the rapid expansion of AM machines and materials has significantly lowered costs, making this technology more accessible. The most employed technology in this field of application was power bed fusion (27%), which offers medical grade materials (like titanium, or biocompatible polyamide) to be used as intra-operative templates, followed by material extrusion (12%), which also offers biocompatible materials, even if with lower printing resolution. Surgical and preclinical education represents the second most studied 3DP application. Surgical training traditionally made use of physical models, animals, or human cadavers. The adoption of both fixed and fresh human specimens in labs has long been and still is a core component in training for ENT surgery, but it has certain limitations such as transmission of infectious agents, exposure to potentially carcinogenic formaldehyde and excessive costs. More recently, 3DP models were used in the teaching of complex anatomy and to simulate critical surgical procedures with particular regard to temporal bone and skull base dissection. The most employed AM technology for this application (Fig. 4) was material extrusion (39%): this is not surprising, since this is the most affordable technology, especially in terms of printing materials. Material extrusion is actually the most suited to apply for teaching and training, where models are usually subjected to damage and need to be produced in high numbers. 25% of studies used power bed fusion machines, thanks to the availability of materials (e.g. polyamide) with mechanical properties that are suitable for drilling and dissection operations. The complexity of temporal bone anatomy and related surgical procedures, essentially based on bone drilling and removal, explain the extensive research on this issue. The evolution of 3DP systems and materials has enabled the reproduction of even the finest chromatic details and mechanical properties of the object resulting in highly representative 3DP simulators. These solutions are unfortunately still expensive, and consequently less employed for the production of didactic devices, as confirmed by the limited use of technologies with high chromatic resolution (binder jetting, 11%) and with tuneable mechanical properties (material jetting, 11%).

Tissue engineering and implantable prostheses is discussed in fewer reports since it represents the most recent 3DP application, but it also entails more exciting future perspectives. The current literature reported the application of 3DP customised titanium alloy prostheses in 33 cases of mandibular reconstruction after tumour resection. Power bed fusion is confirmed as the most widely employed technology in the field, used in 50% of studies: the most common materials are titanium and cobalt-chrome, which are also widely employed in implant standard manufacturing. Preliminary data have provided encouraging results in terms of safety and effectiveness, opening new frontiers of investigation. Nowadays, AM technology has been involved in the production of biocompatible matrices aimed to be cellularised (scaffold), hence forming a new functional tissue. ENT scaffold research is at present confined to a preclinical stage (in vitro and animal testing), with relevant applications in the reconstruction of the upper aerodigestive tract, replacement of tympanic membrane and plastic rebuilding of auricular and nasal cartilages. Even though scaffold research is in its infancy, it represents a future direction of high interest. New perspectives will concern the microstructure of 3DP scaffolds to overcome many currently unsolved questions as well as proper vascularisation to avoid cell degeneration and adequate stem cell proliferation/specialisation. The final goal would entail functional aspects to produce functional tissues and organs by involvement of multiple types of cells and biomaterials.

Moreover, in the foreseeable future, technical advancements will possibly provide a better solution to issues involving biocompatibility and sterilisation protocols of 3DP materials.

Conclusions

3DP systems have revolutionised prototyping in the industrial field by lowering production time from days to hours and costs from thousands to only a few dollars. Today, 3D printers are no longer confined to prototyping, but are increasingly employed in the medical discipline with fascinating results, even in many aspects of otorhinolaryngology. Nevertheless, current reports are still limited to small case-series of patients and lack of comparative objective data to validate 3DP technology in daily clinical practice. 3DP bioengineering is at the beginning of an exciting research field, and the positive results to date are far from what it will be possible to achieve in forthcoming clinical applications.

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