3D printing in dentistry

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IN BRIEF

- Discusses the latest technologies in 3D imaging and printing that can be applied in dentistry.
- Suggests these technologies could be used in daily practice.

PRACTICE

3D printing has been hailed as a disruptive technology which will change manufacturing. Used in aerospace, defence, art and design, 3D printing is becoming a subject of great interest in surgery. The technology has a particular resonance with dentistry, and with advances in 3D imaging and modelling technologies such as cone beam computed tomography and intraoral scanning, and with the relatively long history of the use of CAD CAM technologies in dentistry, it will become of increasing importance. Uses of 3D printing include the production of drill guides for dental implants, the production of physical models for prosthodontics, orthodontics and surgery, the manufacture of dental, craniomaxillofacial and orthopaedic implants, and the fabrication of copings and frameworks for implant and dental restorations. This paper reviews the types of 3D printing technologies available and their various applications in dentistry and in maxillofacial surgery.

INTRODUCTION

The term 3D printing is generally used to describe a manufacturing approach that builds objects one layer at a time, adding multiple layers to form an object. This process is more correctly described as additive manufacturing, and is also referred to as rapid prototyping.[1,2]

3D printing technologies are not all new; many modalities in use today were first developed and used in the late 1980s and 1990s[3] the author first treated a patient with the help of 3D printing in 1999 (Fig. 1).

The term '3D printing', however, is relatively new, and has captured the public imagination. A great deal of hype surrounds the use of 3D printing which is hailed as a disruptive technology that will forever transform manufacturing. We have seen headlines in the international press describing the use of 3D printing to produce everything from fashion wear and architectural models to armaments (Fig. 2). However, the reality is different; 3D printed underwear would today be uncomfortable and 3D printed guns are dangerous – to the individual firing them. While we are very many

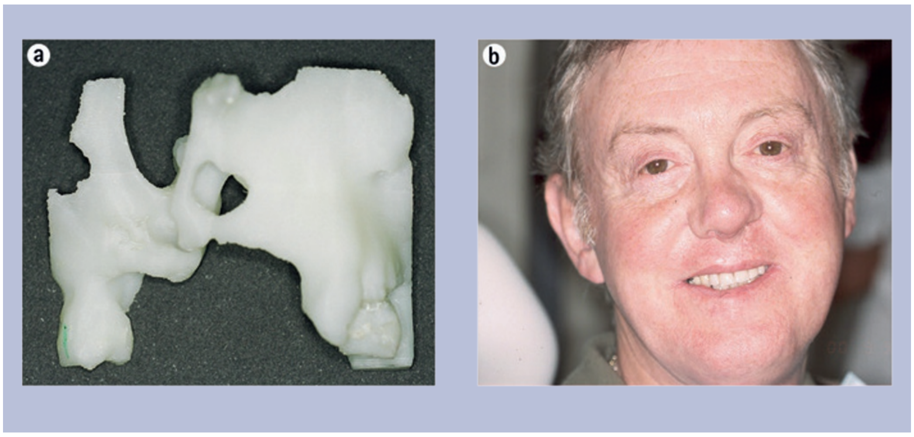

Fig. 1 The first patient treated by the author with the help of 3D printing in 1999. (a) Frontal view of the 3D printed medical model, printed with FDM technology, which shows the complex anatomy of the patient's cleft palate, before implant placement. (b) A recent image of the patient with implant supported bridgework in place

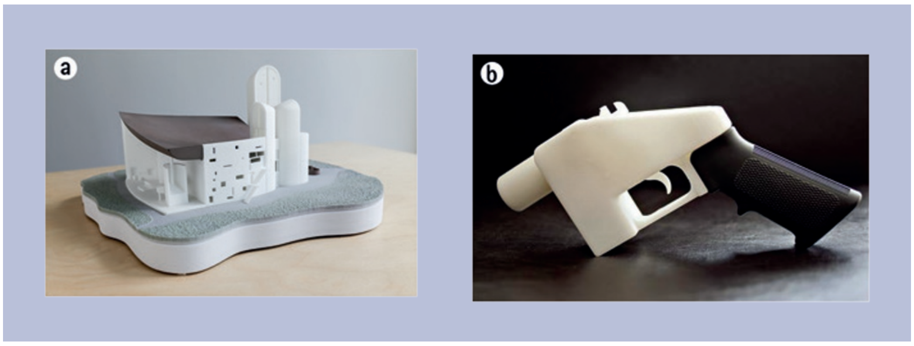

Fig. 2 (a) A 3D printed colour plaster architectural model of one of the most iconic examples of twentieth-century religious architecture designed by Le Corbusier. Model printed by digits2widgets.com. Photograph Chris Sullivan. (b) 3D printed gun. Production file controversially disseminated on the internet by American Cody Wilson, produced by digits2widgets.com for London's Victoria and Albert Museum collection

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years away from seeing the production of viable 3D printed organs, dentistry and oral and maxillofacial surgery have used 3D printing for years, and have whole-heartedly embraced the use of digital manufacturing technologies, notably, the use of computer-aided design and manufacturing. This article sets out to explore why 3D printing is important to dentistry, and why dentistry motivates development in 3D printing applications.

3D PRINTING TECHNOLOGY

From a mechanical perspective, 3D printers are often quite simple robotic devices. The apparatus would be nothing without the computer-aided design (CAD) software that allows objects, and indeed whole assemblies to be designed in a virtual environment. CAD software is commonplace in industrial design, engineering, and manufacturing environments, and is also common in the dental laboratory; it is even becoming a feature of many dental surgeries (Fig. 3).

Developments in computer technology and software applications are very much a part of the groundswell of technological change that has taken 3D printing to where it is today. For 3D printing to have value we need to be able to create objects to print; CAD software allows us to create objects from scratch,[4,5] but in dentistry and surgery we also have ready access to volumetric data in the form of computed tomography (CT) data, cone beam computed tomography (CBCT) data, and intraoral or laboratory optical surface scan data. Recent developments in CBCT and optical scan technology, in particular, have revolutionised, and are profoundly changing many aspects of restorative and implant dentistry. These powerful technological tools are at the disposal of a class of individuals – dentists and dental technicians – who are often polymaths, having a broad level of creativity and an understanding of technology, including engineering and materials skills that extend well beyond that of many others working in individual fields of endeavour.

Dentistry has a long association with subtractive manufacturing[6]– more usually described as 'milling'. Subtractive manufacturing is the removal of material to form an object. CAD CAM for the milling of crown copings and bridge frameworks is now synonymous with modern dental technology.[5] Modern dentistry has a familiarity with materials designed to work with CAD CAM and to substitute for the more traditional precious metal casting alloys,[7] which have been subject to exponential price increases in recent years. This use of technology facilitates the use of materials, which would otherwise be hard to work with, and eliminates labour intensive artisanal production techniques,[8] allowing the dental technician to focus his manual skills on more creative aspects of the manufacturing process, for example the aesthetic layering of porcelain.

Of course every time that a dentist operates to provide a restoration or reconstruction, the procedure is unique to that patient, that jaw, that tooth, or that implant. The reconstruction or restoration will also have innate complexity requiring the reproduction of convoluted geometry with a high level of precision.[9] Although multi-axis CAD CAM milling processes will allow this to an extent,[10] the process is slow and wasteful as the material is milled from an intact block, and accuracy is limited by the complexity of the object, the size of the tooling, and the properties of the material. 3D printing, however, comes into its own for the accurate one-off fabrication of complex structures in a variety of materials with properties that are highly desirable in dentistry and in surgery.[11]

APPLICATIONS OF 3D PRINTING IN DENTISTRY AND ORAL AND MAXILLOFACIAL SURGERY

Medical modelling

One of the earliest applications of 3D printing in surgery, medical modelling, may be thought of as the production of an anatomical 'study model'.[12] This has been made all the more accessible by another important technology that has become mainstream in dentistry in recent years; CBCT has become widely available in dental practices[13,14] and has transformed diagnosis and treatment in implant dentistry[15,16] and in endodontics.[17-19] Ready access to CT, which provides similar data and is more prevalent in a hospital setting, or CBCT means that it is possible to provide volumetric 'image' data to a 3D printer before surgery[20] and to make detailed replicas of the patient's jaws. This allows anatomy, particularly complex, unusual, or unfamiliar anatomy, to be carefully reviewed and a surgical approach planned or practised before surgery.[21,22]

This has led to the development of new procedures and approaches to surgery[23] and along with the production of drilling or cutting guides using 3D printed technology or conventional laboratory technology, can lead to expedited, less invasive, and more predictable surgery[24,25] (Fig. 4).

For medical modelling, accuracy will often be constrained by the original imaging modality and the presence of artefact[26] caused by metal structures such as teeth, restorations or implants; the level of inaccuracy is unlikely to be clinically relevant for many surgical applications. A wide variety of 3D printers and 3D printing materials can be used to print medical models, but as it is useful to have such models in the operating room, materials that can be sterilised, such as nylon, are particularly interesting.[27]

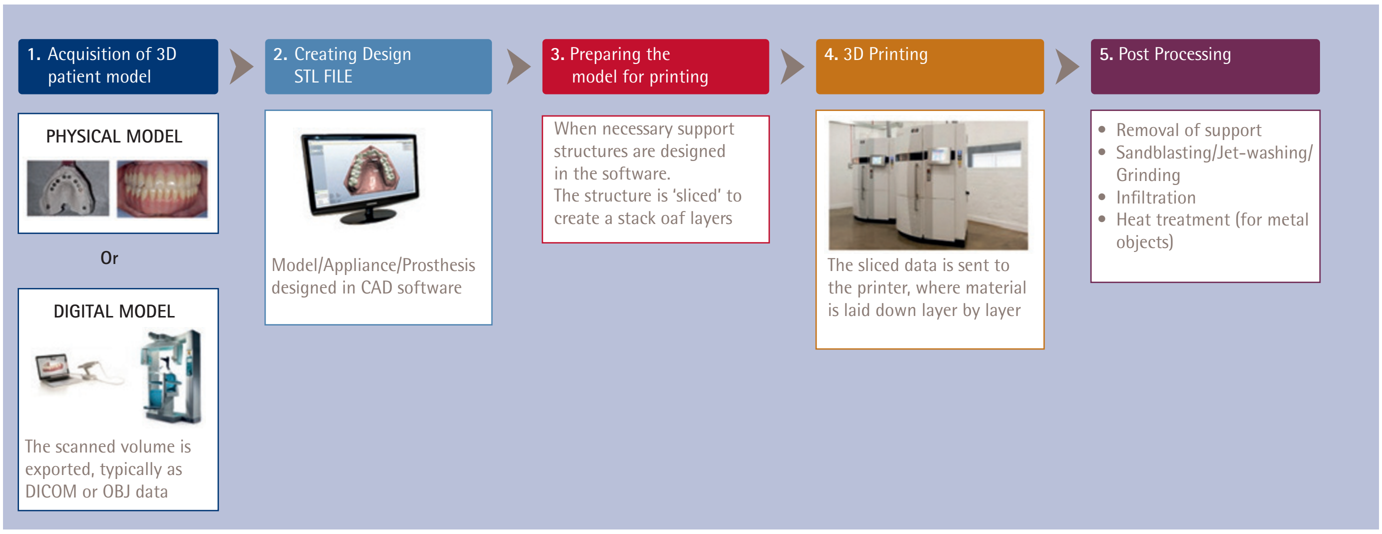

Fig. 3 3D printing process

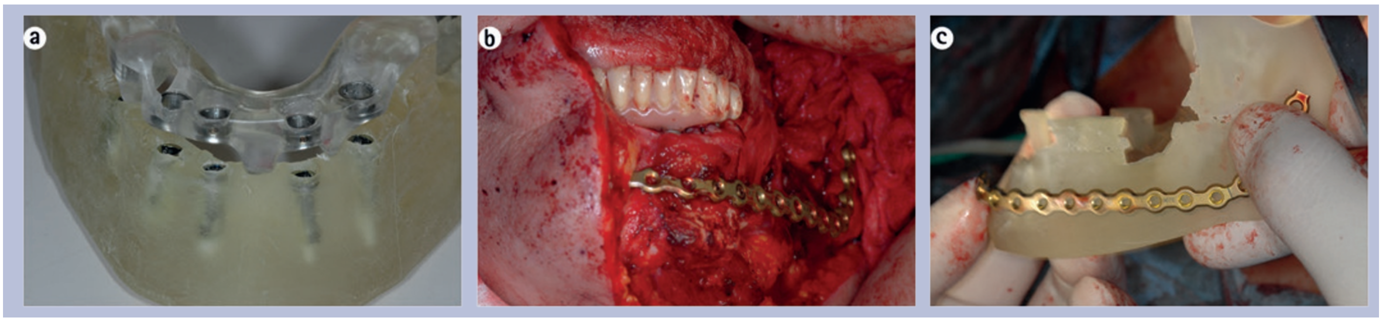

Fig. 4 Models and drill guides printed in resin for simultaneous Full lower arch implant rehabilitation and mandibular reconstruction. (a) Implant drill guide over the 3DP model. (b) Bending the osteosynthesis plate on the sterilised medical model. (c) Plate in place.

Drilling and cutting guides

These 'engineering' tools need to be robust and precise, as well as being capable of sterilisation or disinfection as used in a surgical environment.[28] The use of drill guides in implant dentistry is becoming commonplace,[29] and this technology has been embraced in orthopaedics for total knee replacement,[30] for example. The use of drill guides and cutting guides allows a virtual 3D plan, created on-screen in software to be transferred to the operative site,[31,32] and as such may be thought of as an interface between the virtual plan and the physical patient (Fig. 5[33]).

Inaccuracy resulting from the scan modality, software, and the presence of artefact may be clinically relevant for dental implant procedures or where prostheses are prefabricated to precisely fit a pre-planned post-operative result.[34] Precise 3D printers and high-resolution printing materials must be utilised for implant drill guides – unfortunately, some of the best materials that may be used for this purpose are not autoclavable.

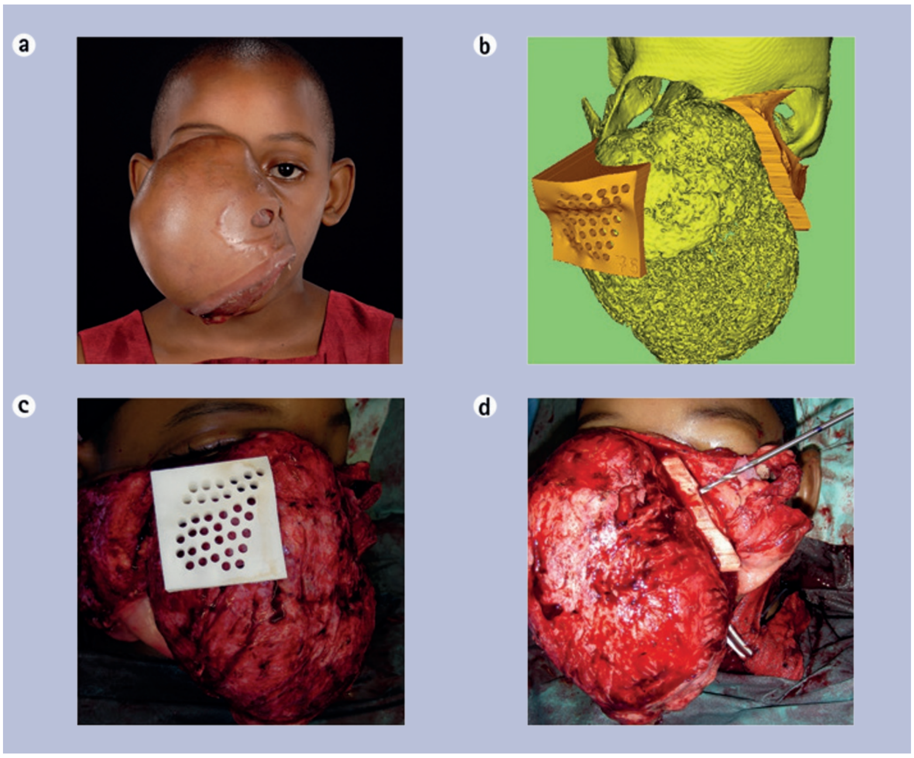

Fig. 5 Use of a 3D printed SLS drill guide to accurately sculpt a facial tumour (fibrous dysplasia)33.(A) Preoperative appearance. (B) Virtual surgical planning. (C) 3D printed drill/sculpting guide in place. (D) Guided drilling with help of a second drilling/sculpting guide

Crown copings and partial denture frameworks

With the use of intraoral optical scanners or laboratory scanners it is possible to develop a precise virtual model[35,36] of the prepared tooth, implant position,[37] and the dental arch.[36,39] In fixed and removable prosthodontics, treatment may be planned and restorations designed in CAD software. This scan data and CAD design may be used to mill or print crown or bridge copings, implant abutments, and bridge structures.

3D printing may be harnessed for the fabrication of metal structures[40] either indirectly by printing in burn-out resins or waxes for a lost-wax process, or directly in metals or metal alloys.[8] The advantage of printing in resin/wax and then using a traditional casting approach is that there is much less post-processing involved than in the direct 3D printing of metals;[41] casting alloys and facilities are also familiar and widely available. Printing directly in metals requires the use of more costly technologies which have their own very specific health and safety requirements, and demand a great deal of post-processing before components may be ready for use[42] (Fig. 6[43]).

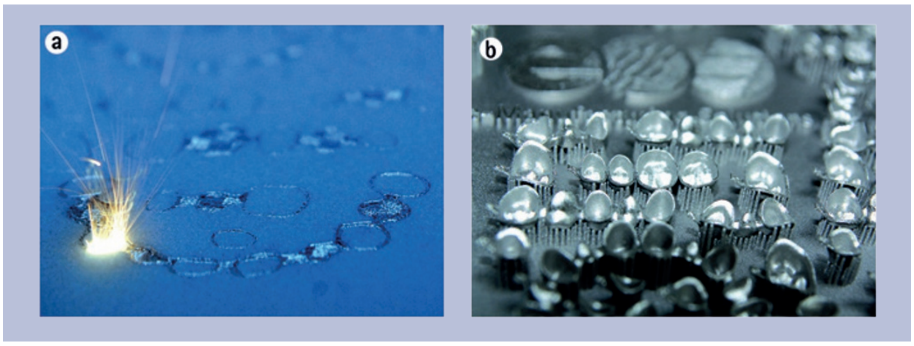

Fig. 6 3D manufacture of metal crown copings. (a) Selective laser sintering in progress. (b) Printed copings in cobalt chrome alloy tethered to build platform by support structue. (Images courtesy of EOS, GmbH)

When printing elaborate implant bridge structures 3D printing may be used in conjunction with milling/machining technologies to produce a high precision mechanical connection to the implant – combining the

Fig. 7 SLS printed prepared teeth, printed from data from an intra oral scanner

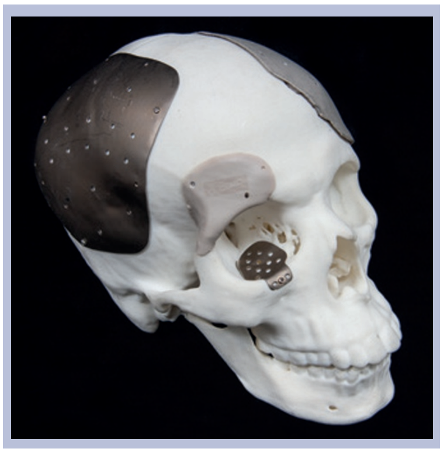

Fig. 8 Cranioplasty and orbital rim implants in titanium or PEEK fitted to a 3D printed SLS model (Courtesy of www.cavendishimplants.com)

best attributes of printing – complex geometry with little waste - with milling – high precision mechanical connecting surfaces.

While it may be somewhat wasteful in material, milling has the advantage that the material used is intrinsically homogeneous and unaffected by operating conditions. There is little need for post-processing, and the equipment is considerably less costly.

Dental models for restorative dentistry

The trend towards the use of intraoral scanners means that dentists need 3D printing in order to make a physical model of the scanned jaw.

Although today, it is not always strictly necessary to print a master model at all,[44] the 3D printed master model (Fig. 7) may be used for conventional aspects of the fabrication of a restoration, such as adding a veneering material, and we are accustomed to seeing restorations displayed on a model – even if they have been directly fabricated digitally. Patient model data may be digitally archived, and only printed when needed, easing storage requirements.

Digital orthodontics

In orthodontics, treatment may be planned and appliances created, or wires bent robotically based upon a digital workflow using intra oral or laboratory optical scanning or even CBCT to capture patient data. The Invisalign®, system digitally realigns the patients teeth to make a series of 3D printed models for the manufacture of 'aligners', which progressively reposition the teeth over a period of months/years.[45,46] An example of printing with multiple materials is in the manufacture of 3D printed, indirect bracket-bonding splints, printed in rigid and flexible materials for precise bracket placement using orthodontic CAD software (3Shape).[47]

As data travels through the internet, and smile design takes place in software, there are huge potential savings in time. Again, patient data may be digitally archived, and only printed when needed, with great savings in physical storage-space requirements.

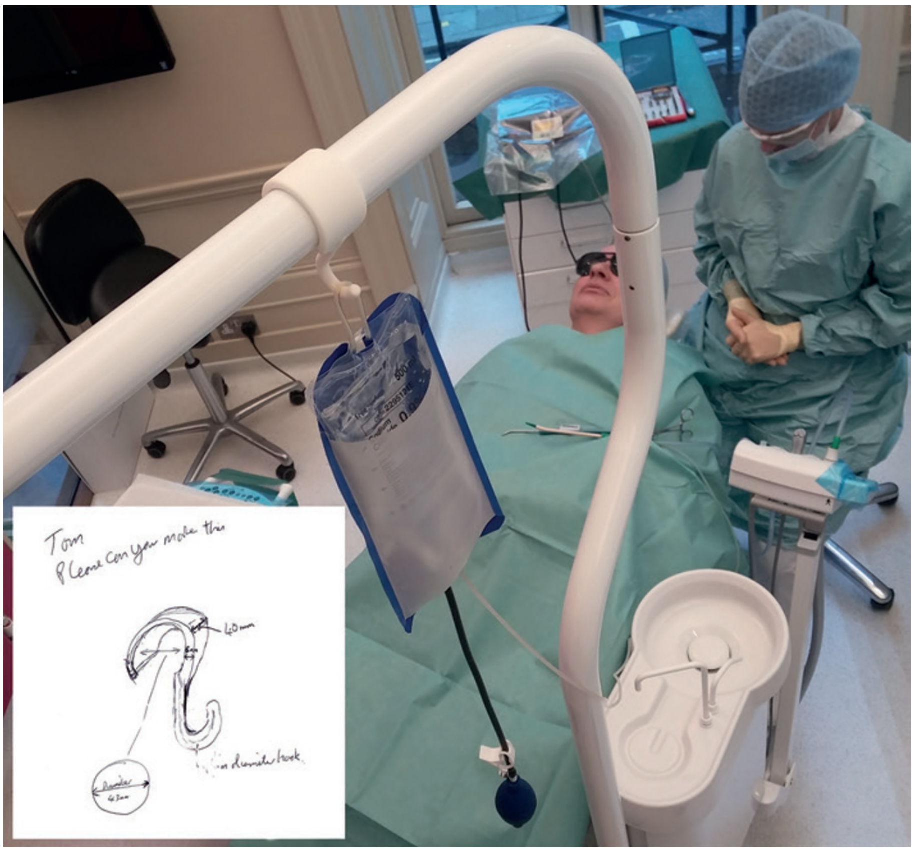

Fig. 9 Back-of-envelope design, leads rapidly to a functional prototype for a 3D printed saline bag holder, fitted to dental chair

Dental implants

Manufacturers have used 3D printing technology to create novel dental implants[32] with a porous or rough surface.[48] We must be careful, however, not to be seduced by the attraction of a rough or porous surface; over the years we have seen many dental implants appear with rough or porous surfaces only to disappear as problems became evident some years later.[49–51] However, as a method for producing batches of complex dental implants, 3D printing has the ability to produce complex geometries, such as a bone-like morphology, which may not be produced by milling alone – although milling/machining may also be used to refine the printed form – for example, the implant platform. There is also the opportunity to create implants which have complex geometry, although ultimately inserting a dental implant using a screw type form seems like a well proven approach.

OMF implants

Much has been made of the ability to print in titanium or in implantable polymers (notably Poly ethyl ether ketone [PEEK][52]) to create maxillofacial implants[53,54] (Fig. 8). 3D printing is capable of producing complex geometries, however, most OMF implants are actually quite simple in form; pressing and milling technologies have several distinct advantages, such as reduced post-processing, quick production, and the predictable use of homogeneous and uniform materials. 3D printing may be used to print the implanted structure directly, or as a tool for indirect manufacture using a conventional pressing process.

Product design and instrument manufacture

Surgeons in general, and dentists certainly, are known for their creativity and ingenuity! 3D printing has a role in the rapid prototyping of instrumentation, which allows creative individuals to take an idea to fruition in a very short period of time. Perhaps a reason why the term 3D printing caught the public's imagination, whereas 'rapid prototyping' never seemed that exciting, is that while the technology allows the surgeon-designer to move rapidly from concept to prototype product, the actual printing process itself is rather slow and costly when working with materials with useful mechanical properties.

The authors have used 3D printing to produce several prototype designs for innovative or mundane instruments or devices used in everyday practice (Fig. 9).

3D PRINTING TECHNOLOGIES AND MATERIALS

Many different printing technologies exist, each with their own advantages and disadvantages (Table 1). Unfortunately, a common feature of the more functional and productive equipment is the high cost of the equipment, the materials, maintenance, and repair, often accompanied by a need for messy cleaning, difficult post-processing, and sometimes onerous health and safety concerns.

Steriolithography (SLA, SL)

A stereolithography apparatus (Fig. 10[55]) uses a scanning laser to build parts one layer at a time, in a vat of light-cured photopolymer resin. Each layer is traced-out by the laser on the surface of the liquid resin, at which point a 'build platform' descends, and another layer of resin is wiped over the surface, and the process repeated.

Supports must be generated in the CAD software, and printed to resist the wiping action and to resist gravity, and must later be removed from the finished product. Post-processing involves removal of excess resin and a hardening process in a UV oven.

The process is costly when used for large objects, but this technology is commonly used for the industrial production of 3D printed implant drill guides.

Photopolymer jetting (PPJ)

This technology uses light cured resin materials and print heads rather like those found in an inkjet printer (but considerably more costly), to lay down layers of photopolymer which are light cured with each pass of the print head.

Table 1 3D printing modalities and materials

Techniques	Advantages	Disadvantages
Light cured resin		
1- Stereolithography (SLA) Light sensitive polymer cured layer by layer by a scanning laser in a vat of liquid polymer	Rapid fabrication. Able to create complex shapes with high feature resolution. Lower cost materials if used in bulk.	Only available with light curable liquid polymers. Support materials must be removed . Resin is messy and can cause skin sensitisation, and may be irritant by contact and inhalation. Limited shelf life and vat life. Can not be heat sterilised. High cost technology.
2- Photojet - Light sensitive polymer is jetted onto a build platform from an inkjet type printhead, and cured layer by layer on an incrementaly descending platform.	Relatively fast. High-resolution, high-quality finish possible. Multiple materials available various colours and physical properties including elastic materials. Lower cost technology.	Tenacious support material can be difficult to remove completetly. Support material may cause skin irritation. Can not be heat sterilised. High cost materials.
3- DLP (digital light processing) Liquid resin is cured layer by layer by a projector light source. The object is built upside down on an incrementally elevating platform.	Good accuracy, smooth surfaces, relatively fast. Lower cost technology.	Light curable liquid polymers and wax-like materials for casting. Support materials must be removed . Resin is messy and can cause skin sensitisation, and may be irritant by contact Limited shelf life and vat life. Can not be heat sterilised. Higher cost materials.
Powder binder		
Plaster or cementaceous material set by drops of (coloured) water from 'inkjet' print head. Object built layer by layer in a powder bed, on an incrementaly descending platform.	Lower cost materials and technology. Can print in colour. Un-set material provides support Relatively fast process. Safe materials.	Low resolution. Messy powder. Low strength. Can not be soaked or heat sterilised.
Sintered powder		
Selective laser sintering (SLS) for polymers. Object built layer by layer in powder bed. Heated build chamberraises temperature of material to just below melting point. Scanning laserthen sinters powder layer by layer in a descending bed.	Range of polymeric materials including nylon, elastomers, and composites. Strong and accuracte parts. Self-supported process. Polymeric materials – commonly nylon may be autoclaved. Printed object may have full mechanical functionality. Lower cost materials if used in large volume.	Significant infrastructure required, eg. compressed air, climate control. Messy powders. Lower cost in bulk. Inhalation risk. High cost technology. Rough surface.
Selective laser sintering (SLS) - for metals and metal alloys. Also described as selective laser melting (SLM) or direct metal laser sintering (DMLS). Scanning laser sinters metal powder layer by layer in a cold build chamber as the build platform descends. Support structure used to tether objects to build platform.	High strength objects, can control porosity. Variety of materials including titanium, titanium alloys, cobalt chrome, stainless steel. Metal alloy may be recycled. Fine detail possible.	Elaborate infrastructure requirements. Extremely costly technology moderately costly materials. Dust and nanoparticle condensate may be hazardous to health. Explosive risk. Rough surface. Elaborate post-processing is required: Heat treatment to relieve internal stresses in printed objects. Hard to remove support materials. Relatively slow process.
Electron beam melting (EBM, Arcam). Heated build chamber. Powder sintered layer by layer by scanning electron beam on descending build platform.	High temperature process, so no support or heat treatment needed afterwards. High speed. Dense parts with controllled porosity.	Extremely costly technology moderately costly materials. Dust may be hazardous to health. Explosive risk. Rough surface. Less post-processing required. Lower resolution.
Thermoplastic		
Fused deposition modelling (FDM) First 3DP technology, most used in 'home' printers. Thermoplastic material extruded through nozzle onto build platform.	High porosity. Variable mechanical strength. Low - to mid-range cost materials and equipment. Low accuracy in low costequipment. Some materials may be heat sterilised.	Low cost but imited materials - only thermoplastics. Limited shape complexity for biological materials. Support material must be removed.

Fig. 10 (a) diagram of SLS printing process (diagram courtesy of EOS, GmbH).[61] (b) Industrial SLS apparatus (image courtesy of www.digits2widgets.com)

Fig. 11 Industrial powder binder printer and example bust of author captured with 3D photography and printed in full colour plaster of Paris (courtesy of www.digits2widgets.com)

The technology may use a stationary platform and dynamic print head or a stationary print head and dynamic platform. A support structure is laid down in a friable support material.

A variety of materials may be printed including resins and waxes for casting, as well as some silicone-like rubber materials. Complex geometry and very fine detail is possible[56]– as little as 16 microns resolution.

The drawback is that the equipment, and materials are costly to purchase and run, and the support materials can be tenacious and rather unpleasant to remove. They are useful for printing dental or anatomical study models, but these are expensive when produced in this way. Implant drill guides may be quickly and cheaply produced with this technology as they are less bulky. A particular advantage of this technology is that the use of multiple print heads allows simultaneous printing with different materials, and graduated mixtures of materials, makes it possible to vary the properties of the printed object, which may for example have flexible and rigid parts, eg for the production of indirect orthodontic bracket splints.

Powder binder printers (PBP)

These apparatus use a modified inkjet head to print using, what is essentially, liquid droplets to infiltrate a layer of powder, layer by layer. Typically a pigmented liquid, which is mostly water, is used to print onto the powder, which is mostly plaster of Paris (Fig. 11).

Again, a model is built up in layers as the powder bed drops incrementally, and a new fine layer of powder is swept over the surface. The model is supported by un-infiltrated powder, and so no support material is required. Post-processing to infiltrate the delicate printed model with a cyanoacrylate or epoxy resin will improve strength and surface hardness.

The resulting models are useful as study models or visual prototypes, but accuracy[47] is limited and the models are rather fragile despite the post-processing. A particular excitement of this technology lies in its ability to print models in full colour; from a surgical perspective the drawback is that the models may not be sterilised or directly manipulated at operation.

Accuracy is inadequate for prosthodontic applications. The machines and materials are lower cost, but still not inexpensive. As the material is mostly plaster of Paris, there is some compatibility with having the apparatus situated in a dental laboratory plaster room.

Selective laser sintering (SLS)[57]

This technology has been available since the mid-1980s.[58] A scanning laser fuses a fine material powder, to build up structures layer by layer, as a powder bed drops down incrementally, and a new fine layer of material is evenly spread[59,60] over the surface. A high (60μm) level of resolution may be obtained, and as the structures that are printed are supported by the surrounding powder, no support material is required.

Polymers used in this process have high melting points (above autoclave sterilisation temperature) and excellent material properties,[61,62] making objects made in this way useful as anatomical study models,[63,64] cutting and drilling guides, dental models, and for engineering/design prototypes. However, some of the materials are difficult to drill and prepare, and the technology is costly to purchase, maintain, and run, therefore requiring copious quantities of compressed air. The materials are intrinsically dusty, have some health and safety requirements, and are rather messy to work with.

Materials available include nylon, which is perhaps the most versatile, flexible elastomeric materials, and metal-containing nylon mixtures. An interesting possibility for medical implants is the use of polyether ether ketone (PEEK),[65] although this requires high temperatures and complex control – and a great deal of wastage.

The ability to 3D print in metals is incredibly exciting in the dental world. There are a broad range of metals and metal alloys available including titanium, titanium alloys, cobalt chrome alloys, and stainless steel. 3D printed partial dentures and prosthesis frameworks are already being made in this way, and for implant bridge frameworks technology may be combined with milling processes to provide high precision connections. The technology is broadly the same as that described for polymers above, but these apparatus may also be described by different manufacturers as, 'selective laser melting', or 'direct metal laser sintering'.

The 3D printing process itself may be straightforward, but post-processing is definitely not straightforward, and the fine metal powders and even finer nanoparticle waste represents quite a significant health and safety challenge. While the printer itself may be readily accommodated in the dental laboratory, the associated post production equipment takes up at least as much space. While in theory the use of one machine to print in different materials may seem feasible, in practice it is extremely difficult to fully clean down a machine, and certainly switching between an implantable metal and a restorative material is not at all practical.

In small batch production the technology is costly and casting continues to have many attractions. However, in a large dedicated machine it is possible to simultaneously print 400–500 crown copings in a 24 hour period. Furthermore, copings may be printed in lower cost materials that are traditionally harder to work with than gold alloys, such as cobalt chrome, but which offer good porcelain bonding strengths and excellent mechanical properties.

In surgical applications, the technology allows for the straightforward batch production of implants for orthopaedic applications,[66] and for dental implants,[67] and has been considered for use in the production of titanium cranioplasties in oral and maxillofacial surgery.[68,69]

Fused deposition modelling (FDM)[70]

FDM is one of the earliest 3D printing technologies and was used by the author to produce his first medical model in 1999. An FDM printer is essentially a robotic glue gun; an extruder either traverses a stationary platform, or a platform moves below a stationary extruder. Objects are 'sliced' into layers by the software and coordinates transferred to the printer. Materials must be thermoplastic by definition. A commonly used material is the biodegradable polymer polylactic acid; this or similar materials have been used as key components of scaffold structures used for 'bioprinting'[71] – a popular area for research in tissue engineering. Building complex geometries usually necessitates the laying down of support structures which may be either formed from the same material, or from a second material laid down by a second extruder – which, for example, might extrude a water soluble support material. Accuracy will depend upon the speed of travel of the extruder, as well as the flow of material and the size of each 'step'.

This is the process that is used by most low cost 'home' 3D printers. It allows for the printing of crude anatomical models without too much complexity,[57] – for example, printing an edentulous mandible might be possible, though printing a detailed maxilla would be a tall order. More costly, more accurate FDM printers are available, and have application in anatomical study-model making, but little else in dentistry or in surgery.

DISCUSSION

The profession is already accepting of digital manufacturing technologies; much of the laboratory work that was once produced by artisan processes is now produced digitally, leaving only the final finishes of restorations to be applied by hand. The use of CAD CAM technology has become commonplace in the dental laboratory, and may be seen more and more in the dental surgery. Whereas early approaches to scanning and the production of digitally manufactured restorations relied upon the use of centralised scanning and manufacturing facilities, many laboratories now have their own laboratory scanners, and many also have their own milling units. In the dental practice environment, intra oral and CBCT scanners are becoming more and more common.

All this means that dentists and dental technicians are becoming well acquainted with, and adept at working with large volumes of digital data. 3D printing offers another form of 'output' device for dental CAD software; making it possible to materialise intricate components and objects in a variety of different materials. It comes into its own when structures are unique, bespoke, have intricate geometry, and where 3D scan data is easily obtained.

In dentistry, 3D printing already has diverse applicability, and holds a great deal of promise to make possible many new and exciting treatments and approaches to manufacturing dental restorations. The national regulatory bodies have not yet implemented guidance in the use of 3D printing in surgery,[72] or in dentistry, but at some stage there will be a need for regulators to focus on this technology to set appropriate standards.

Although 3D printing apparatus and technologies have been readily available for more than a decade, it is developments in, and access to scanner technology, computer-aided design software and raw computational power, that has started to make the use of the technology practical, while commercial and public interest has raised awareness and improved access to resources.

With the introduction of milling technology, a plethora of new material options became available for the production of restorations; similarly, new generations of dental restorative materials for 3D printing are under development and appearing on a regular basis.

Taking into account the range of indications for 3D printing in dentistry, and the profession's long experience of scanning and milling technology, it might be said that dentists and dental technologists have a broader experience of these 3D manufacturing technologies than any other profession.

CAD software is still the domain of the well-trained and computer literate, but this will not faze new generations of operator, and the software is becoming 'smarter' and more user-friendly all the time. Key future developments that would drive forwards our usage of the technology beyond the obvious benefits of reduced costs, increased speed of manufacture, and faster, less invasive treatments for our patients, include the potential to 3D print in ceramic materials with digital colouration and staining, the reduction of the post-processing needed for metal parts, and the integration of machining/milling of 3D printed metal parts into the metal printing workflow.

All of this means that the slowly evolving use of digital technologies in dentistry has gathered momentum to the point that we are, in the opinion of the authors, long past the point of early adoption, with the opportunity for mainstream use of 3D printing technology in the orthodontic and dental laboratory, and in surgery. There is scope for so much more development; while there is a great focus on individual items of equipment, it is the overall integration of the equipment with the planning and design software to create a smooth, rigorous and streamlined workflow that is of key importance, and will make all the difference to the uptake and acceptance of these disruptive technologies.

Along with this new technology comes new opportunity; the challenge that we face is to not look at 3D printing as a new tool to do what we have always done, but to look at it as a technology that will allow us to be more creative, to develop new materials and new more predictable, less invasive and less costly procedures for our patients. We must also avoid being seduced by this and other aspects of digital technology into thinking that because it is digital, it is better; research is needed to define standards and make sure that the equipment that is rapidly finding its way into our laboratories and into our surgeries performs at least as well as current conventional 'analogue' processes.

CONCLUSION

3D imaging and modelling, and CAD technologies are hugely impacting on all aspects of dentistry. 3D printing makes it possible to accurately make one-off, complex geometrical forms from this digital data, in a variety of materials, locally or in industrial centres. Even now, nearly everything we make for our patients can be made by a 3D printer, but no single technology is sufficient for all our patient's needs. The technology is already widely used in orthodontics, where high-resolution printing in resin is already an entirely practical proposition, and similar technology is being used to print models for restorative dentistry and patterns for the lost wax process which is becoming increasingly important with the rise of intraoral scanning systems. In maxillofacial and implant surgery, it is becoming commonplace and prerequisite to use anatomical models made by any number of different 3D printing techniques to assist with the planning of complex treatments. It is widely acknowledged that surgery may be less invasive and more predictable with the use of surgical guides printed in resins (commonly) or autoclavable nylon. For many, the real excitement will be in the direct production of metal-based restorations for implants and teeth, but this is yet to become routine in the dental laboratory in the UK.

Although 3D printers are becoming more affordable, the cost of running, materials, maintenance, and the need for skilled operators must also be carefully considered, as well as the need for post-processing and adherence to strict health and safety protocols. Despite these concerns it is clear that 3D printing will have an increasingly important role to play in dentistry. The congruence of scanning, visualisation, CAD, milling and 3D printing technologies, along with the professions innate curiosity and creativity makes this an exceptionally exciting time to be in dentistry.

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