Biotechnology Advances 35 (2017) 521–529

Contents lists available at ScienceDirect

Biotechnology Advances

journal homepage: www.elsevier.com/locate/biotechadv

Research review paper

Three-dimensional printing: technologies, applications, and limitations in neurosurgery

Josephine U. Pucci*, Brandon R. Christophe, Jonathan A. Sisti, Edward S. Connolly Jr.

Columbia University Medical Center Department of Neurological Surgery, 710 W 168th Street, New York, NY 10032, United States

ARTICLE INFO

Keywords:
3D printing
Additive manufacturing
Computer-aided design
Fused deposition modeling
Material jetting
Neurosurgery
Stereolithography
Three-dimensional printing
Solid modeling

ABSTRACT

Three-dimensional (3D) printers are a developing technology penetrating a variety of markets, including the medical sector. Since its introduction to the medical field in the late 1980s, 3D printers have constructed a range of devices, such as dentures, hearing aids, and prosthetics. With the ultimate goals of decreasing healthcare costs and improving patient care and outcomes, neurosurgeons are utilizing this dynamic technology, as well. Digital Imaging and Communication in Medicine (DICOM) can be translated into Stereolithography (STL) files, which are then read and methodically built by 3D Printers. Vessels, tumors, and skulls are just a few of the anatomical structures created in a variety of materials, which enable surgeons to conduct research, educate surgeons in training, and improve pre-operative planning without risk to patients. Due to the infancy of the field and a wide range of technologies with varying advantages and disadvantages, there is currently no standard 3D printing process for patient care and medical research. In an effort to enable clinicians to optimize the use of additive manufacturing (AM) technologies, we outline the most suitable 3D printing models and computer-aided design (CAD) software for 3D printing in neurosurgery, their applications, and the limitations that need to be overcome if 3D printers are to become common practice in the neurosurgical field.

1. Introduction

3D Printing is an additive manufacturing (AM) method, which, upon receiving computer-aided designs (CAD), methodically constructs three-dimensional structures from successive layers (Bártolo and Gibson, 2011; Jacobs, 1992; Lipson and Kurman, 2013). AM offers advantages over traditional subtractive and formative methods as it can create intricate designs of complex structures while utilizing a wide range of materials, including plastic, metal, wax, rubber, wood, cloth, food, and biomaterial (Cooper, 2001; Kruth, 1991; Mironov et al., 2011; Mironov et al., 2003). 3D printing has integrated itself into numerous markets as printers progress from building simple parts and prototypes to creating fully functional components and end products, such as batteries (Cohen et al., 2014; Weller et al., 2015). The AM industry was sized at 2.2 billion in 2012 (Reeves, 2014), 5.2 billion in 2015, and is estimated to reach 8.8 billion in 2017 (J.P.Morgan, 2016). The constant improvements of this dynamic model make the transition to the medical field a natural progression. In 2013, the medical/dental sector accounted for 16.4% of the industry's total revenue, behind only consumer products and motor vehicles at 21.8% and 18.6%, respectively (Misek et al., 2013). In a rapidly growing field with dozens of manufacturers, 3D printing models range from 3D consumer desktop printers that sell as low as a couple hundred dollars to mass manufacturing machines that could cost well over one million dollars (Table 1, sources: (Anderson et al., 2015; Berman et al., 2012; Frölicha et al., 2016; Kimura et al., 2009; Kondo et al., 2015; Krueger and Barr, n.d.; Lan et al., 2016; Misek et al., 2013; North and Kisner, 2015, 2014; Ryan et al., 2016; Thawani et al., 2016)). Each printing method offers its own advantages and disadvantages, such as length of time to build, materials used, precision, and durability. Currently, there is no standard printing process for patient care and medical research. In an effort to enable neurosurgeons to optimize the use of additive manufacturing (AM) technologies, we outline important considerations for choosing a 3D printing device, the steps for creating a 3D model with computer-aided design (CAD) software, the medical applications of 3D printed models, and the limitations that must be overcome if 3D printer use is to become common practice in the neurosurgical field.

Abbreviations: 3D, Three-dimensional; AM, Additive manufacturing; CAD, Computer-aided designs; DICOM, Digital Imaging and Communication in Medicine; FDM, Fused Deposition Modeling; GM, Gross margin; MJM, Multi-Jet Modeling; PEKK, Polyetherketoneketone; SLA, Stereolithography (printing method); STL, Stereolithography (file format)

* Corresponding author.
E-mail addresses: jup2102@cumc.columbia.edu (J.U. Pucci), brc2119@cumc.columbia.edu (B.R. Christophe), jas2269@cumc.columbia.edu (J.A. Sisti), esc5@cumc.columbia.edu (E.S. Connolly).

http://dx.doi.org/10.1016/j.biotechadv.2017.05.007
Received 30 August 2016; Received in revised form 1 May 2017; Accepted 22 May 2017
Available online 24 May 2017
0734-9750/

Biotechnology Advances 35 (2017) 521–529

Table 1
Three-dimensional printers: technologies and applications.

Process	Technology/Brand Names	Build materials	Materials	Printing processes	Selected companies	ASP	Applications	Selected published neurosurgery papers
Material Extrusion	Fused Deposition Modeling (FDM)	Material Deposited	Plastic (typically ABS or PLA)	Extrusion Model	Stratasys (MakerBot, Fortus); Ultimaker; RepRap (open-source)	Most $400–$4000; Up to 500K	tooling; prototypes	Anderson et al. (2015); Ryan et al. (2016); Frölicha et al., 2016
Vat photopolyerization	Stereolithography (SLA)	Liquid material hardened	Liquid plastic	light/laser/ electron beam	3D Systems (Projet 6000/7000; Envisiontec, Carima, DWS; prodways	$3K–$800K	prototypes, casting, tooling	Kimura et al. (2009); Thawani et al. (2016)
Material jetting	Polyjet/Multi-Jet Modeling	Material Deposited	Liquid Plastic; Wax	Inkjet Printhead	Stratasys (Objet Connex; 3D Systems (Projet)	$20K–$600 K	dental, prototypes	Lan et al. (2016); Erbano et al. (2013)
Powder bed binder jetting	3DP (DDD)	Powdered Material Bonded/ Fused	Sand; Plastic; Metal; Plaster	Inkjet Printhead	3D System (Z Corp, ProJet), ExOne, voxeljet	$16K–$1.8M	casting, auto, dental, aerospace, energy	Ryan et al. (2016); Kondo et al. (2015)
Powder bed fusion	Selective laser sintering (SLS); Direct metal laser sintering (DMLS)	Powdered material bonded/ fused	Plastic; metal; sand	Light/Laser/ Electron beam	EOS, 3D System (sPro, Phenix, ProX); Concept Laser GmbH (LaserCURING); Ricoh; Prodways	$170 K - $1.7 M	Dental, medical tools, aerospace, auto	
Directed energy deposition	Laser-engineered net shaping (LENS)		Metal		Optmec	$350 K - $1.5 M	repair	
Sheet lamination	Selective Deposition Lamination (SDL); Ultrasonic Additive Manufacturing (UAM)		Paper; metal		Mcor (SDL); Fabrisonic (UAM)	$37 K +	SDL: consumer, prototypes; UAM: cladding	

*Sources cited in paper.

2. Choosing a three-dimensional printer

To optimize the use of AM technologies, clinicians should be aware of the varying strengths and weaknesses of devices and choose a suitable model based on his or her clinical needs. Here, we discuss examples of 3D printers that could best fulfill a neurosurgeon's needs (Table 2, sources: ("ProJet® 6000 SD | 3D Systems,", n.d., "Replicator Desktop 3D Printer | MakerBot,", n.d.; Stratasys Ltd., n.d.)). A model is included in each of the liquid-based technologies – Fused Deposition Modeling (FDM), Stereolithography (SLA), and Multi-Jet Modeling (MJM) – which are often utilized in surgical fields related to the head and neck (Ide et al., 2016).

2.1. Makerbot Replicator – Makerbot

How it works: a spool wound with plastic filament is heated and extruded through the nozzle. It quickly solidifies as it is methodically deposited onto a build platform. The extrusion head moves in the x-y plane until a layer is complete. Removable material is deposited and acts as scaffolding where support or buffering is needed. Before the model or part is ready to use, the user breaks away support material or dissolves it in detergent and water ("FDM Technology,", n.d.; Misek et al., 2013) (See Fig. 1a, source: (Lockwood et al., 2014); See Fig. 1b, source: ("Replicator Desktop 3D Printer | MakerBot,", n.d.)).

Makerbot uses FDM, which was invented by Stratasys founder Scott Crump in 1989. Stratasys went on to acquire Makerbot, which represents the largest installed base of 3D printers (Misek et al., 2013). FDM generally targets the consumer market, but Makerbot is leveraged toward prosumer/education. This easily operated and maintained desktop model can benefit clinicians who lack an expertise in software and engineering. Both the printer and the environmentally friendly polylactic acid (PLA) filament are very inexpensive compared to other AM processes and materials. However, FDM's surface finish is not very smooth, has a lower resolution on the z axis (Ide et al., 2016), and is one of the slower AM processes as FDM's printing duration could take days, depending on the size, complexity, and resolution of the printed object.

Because of the filament's durability, FDM's strength lies in producing strong thermoplastics and biocompatible materials ("Makerbot Replicator,", n.d.). To date, several surgical papers claim FDM's "feasibility" in creating bones, implants, and even vessels, which is surprising due to the printers' limited material options (Anderson et al., 2015; Bangeas et al., 2016; Mashari et al., 2016; Mowry et al., 2015). Some investigators went as far to suggest that FDM resolution is not only sufficient for aneurysm models (Anderson et al., 2015), but can also be incorporated into vascular flow models (Frölicha et al., 2016; Mashari et al., 2016).

Anderson et al. (2015) used Makerbot Replicator 2 to create 10 aneurysm models. The aneurysm diameters of their designs portrayed accurate dimensions as there was no statistically significant difference compared to source images. Vessels were hollow, which enabled flow phantom testing. Investigators claimed the printed objects were cost-effective and prepared in a timely manner; however, they failed to mention the exact cost and time necessary to build. The authors acknowledged that wall compliancy could be a limitation, especially when attempting to replicate models with varying wall thicknesses due to diseases (Anderson et al., 2015). Although Makerbot may be limited due to material and resolution options, it translates CAD images into 3D form more cheaply and easily than other AM processes.

2.2. Projet 6000 (3D Systems)

How it works: the AM apparatus solidifies three-dimensional objects by polymerizing a fluid medium that is methodically laid in successive layers (Hull, 1986; Lipson and Kurman, 2013). A mirror reflects a UV laser into a vat of liquid plastic, usually referred to as resin, which is