CHEST

Three-dimensional Printing and 3D Slicer

Powerful Tools in Understanding and Treating Structural Lung Disease

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VIDEO

Recent advances in the three-dimensional (3D) printing industry have enabled clinicians to explore the use of 3D printing in preprocedural planning, biomedical tissue modeling, and direct implantable device manufacturing. Despite the increased adoption of rapid prototyping and additive manufacturing techniques in the health-care field, many physicians lack the technical skill set to use this exciting and useful technology. Additionally, the growth in the 3D printing sector brings an ever-increasing number of 3D printers and printable materials. Therefore, it is important for clinicians to keep abreast of this rapidly developing field in order to benefit. In this *Ahead of the Curve*, we review the history of 3D printing from its inception to the most recent biomedical applications. Additionally, we will address some of the major barriers to wider adoption of the technology in the medical field. Finally, we will provide an initial guide to 3D modeling and printing by demonstrating how to design a personalized airway prosthesis via 3D Slicer. We hope this information will reduce the barriers to use and increase clinician participation in the 3D printing health-care sector.

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With three-dimensional (3D) printers, digital surface models are readily made into physical models to allow rapid prototyping. 3D printing has been increasingly applied to medical disciplines in which therapeutic interventions heavily depend on appreciation of complex anatomic structural relationships.[1] This article aims to provide an overview of 3D printing technology and its applications in pulmonary medicine. More specifically, we will focus on how to use a medical image analysis program—3D Slicer (Surgical Planning Laboratory)—to provide pulmonary physicians the ability to generate digital airway models to aid in their daily practice.

Overview of 3D Printing

3D printing technology has been in existence since the 1980s. Charles "Chuck" Hull, cofounder of 3D Systems, is credited with the invention of the world's first 3D printer (stereolithography) in 1983. In the mid to late 1980s, there was a proliferation of 3D printing technology. In 1987, Dr Carl

ABBREVIATIONS: 3D = three-dimensional; FDA = US Food and Drug Administration; PCL = polycaprolactone; PLA = polylactic acid; PLGA = poly lactic-*co*-glycolic acid; SLS = selective laser sintering

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Deckard developed the selective laser sintering (SLS) process. In 1989, Scott Crump invented fusion deposition modeling and went on to cofound Stratasys. Today, these two companies, 3D Systems and Stratasys, are the leaders in the 3D printing industry.[2]

Additive manufacturing via 3D printing has several variations (Fig 1). The most commonly available 3D printing technologies are stereolithography, SLS, fused deposition modeling, and multijet modeling. First, stereolithography (3D Systems; Formlabs) uses a laser to generate an ultraviolet beam at the surface of a pool of photosensitive resin, which leads to local polymerization of the liquid resin. The reaction platform is raised or dropped as each layer is created. This method offers high geometric accuracy but is limited by the resin material available for use (Fig 1A, Video 1).[3] Second, SLS (3D Systems) uses a high-power laser (carbon dioxide) to fuse thermoplastic powder made from plastic, metal, or ceramic. After laser fusing a cross-section, the powder bed drops down one layer thickness, and a new layer of thermoplastic powder is applied. This method allows a variety of materials to be used and affords high accuracy and resolution but at a higher cost (Fig 1B). Third, fused deposition modeling (Stratasys) uses various filaments (acrylonitrile butadiene styrene, polylactic acid [PLA], polycarbonate, polyamides, polystyrene) that are forced through a heated extrusion nozzle, which melts the filaments on a platform bed. The printer nozzle moves in an x-y-z plane and deposits layer after layer of material that hardens after extrusion. This method provides high geometric accuracy and models that can be sterilized for use in an operative setting (Fig 1C, Video 2). Fourth, multijet modeling (Z Corporation) uses layers of fine powder (plaster or resin) that is bonded by water-based adhesive. This method allows full-color prototyping but at the sacrifice of geometric accuracy and mechanical strength (Fig 1D).[2]

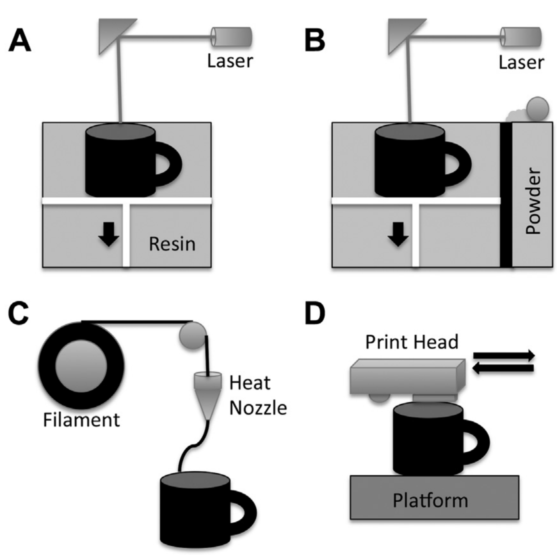

Figure 1 – *A, Stereolithography involves using a laser light source to solidify a photopolymer resin at the focal point where laser hits the polymer. The platform descends (black arrow) after each layer is complete. B, Selective laser sintering involves using a laser-based heat source to sinter layer by layer of powder on a descending platform (black arrow). C, Fusion deposition modeling involves using filaments of thermoplastic polymers extruded through a heated nozzle and deposited on a platform. D, Multijet modeling involves using multiple nozzles to lay down layers of powder and binding agent to print in three dimensions.*

3D Printing Materials

3D printing materials vary depending on the 3D printer used. 3D printable materials that are approved by the US Food and Drug Administration (FDA) for other medical applications include, but are not limited to, polycaprolactone (PCL), PLA, and poly lactic-*co*-glycolic acid (PLGA). These medical polymers can be used alone or blended to achieve desired properties. PCL has a long history of medical applications attributed to its low melting temperature of approximately 60°C, low glass transition temperature of −60°C, and high thermal stability. PCL has been used in both fusion deposition modeling and SLS printers for manufacturing of biological scaffolds for tissue engineering.[4,5] Initially synthesized in the 1920s, PLA is biodegradable thermoplastic aliphatic polyester derived from renewable resources such as corn, sugarcane, roots, or starch. This versatile bioplastic degrades into lactic acid and has been used for implantable screws, mesh, rods, and scaffolds for bone regeneration.[6] PLGA is a copolymer of PLA and polyglycolic acid that is biocompatible and biodegradable and exhibits broad erosion times with modifiable mechanical properties. Depending on the blending ratio of PLA and polyglycolic acid, the resulting PLGA copolymer has very different mechanical properties and degradation profiles. PLGA has been used for extended drug delivery because it degrades via hydrolysis into lactic and glycolic acid.[7,8] A recent review examined in detail the advances in 3D printing biomaterials.[9]

3D Printing and Medical Applications

Beginning in the 1990s, 3D printing found applications in oral and maxillofacial surgery,[10] neurosurgery,[11] and orthopedics.[12] As the technology matured, imaging techniques kept pace. Investigators were able to use