Technical Report

Understanding Spatially Complex Segmental and Branch Anatomy Using 3D Printing: Liver, Lung, Prostate, Coronary Arteries, and Circle of Willis

Ramin Javan, MD, Douglas Herrin, BS, Ardalan Tangestanipoor, MD

Abbreviations

3D
three-dimensional

MRI
magnetic resonance imaging

MRA
magnetic resonance angiography

2D
two-dimensional

STL
standard tessellation language

Rationale and Objectives: Three-dimensional (3D) manufacturing is shaping personalized medicine, in which radiologists can play a significant role, be it as consultants to surgeons for surgical planning or by creating powerful visual aids for communicating with patients, physicians, and trainees. This report illustrates the steps in development of custom 3D models that enhance the understanding of complex anatomy.

Materials and Methods: We graphically designed 3D meshes or modified imported data from cross-sectional imaging to develop physical models targeted specifically for teaching complex segmental and branch anatomy. The 3D printing itself is easily accessible through online commercial services, and the models are made of polyamide or gypsum.

Results: Anatomic models of the liver, lungs, prostate, coronary arteries, and the Circle of Willis were created. These models have advantages that include customizable detail, relative low cost, full control of design focusing on subsegments, color-coding potential, and the utilization of cross-sectional imaging combined with graphic design.

Conclusions: Radiologists have an opportunity to serve as leaders in medical education and clinical care with 3D printed models that provide beneficial interaction with patients, clinicians, and trainees across all specialties by proactively taking on the educator's role. Complex models can be developed to show normal anatomy or common pathology for medical educational purposes. There is a need for randomized trials, which radiologists can design, to demonstrate the utility and effectiveness of 3D printed models for teaching simple and complex anatomy, simulating interventions, measuring patient satisfaction, and improving clinical care.

Key Words: 3D printing; anatomy; radiology; education; 3D model.

INTRODUCTION

Three-dimensional (3D) printing is contributing to the revolution of personalized and precision medicine (1). The use of 3D products in medicine is burgeoning (2–9): planning surgical procedures for hepatic and renal cancer removal; innovative cardiac and vascular device testing for pediatric and adult populations; visualization of complex head and neck anatomy for neurosurgeons and neurologists; practicing spine and lung procedures ex vivo for residents and medical students; personalized drug tablets and delivery with potential for nanotechnology; training models for image guided spinal pain management; and educating medical providers and the patients.

Patient-customized 3D products are available because of advanced 3D printing in conjunction with the evolution of cross-sectional imaging (2,6,10), which includes high-resolution multidetector computed tomography, computed tomography angiography, steady-state free precession and fast spoiled gradient-echo, magnetic resonance imaging (MRI), and magnetic resonance angiogram (MRA). Similar to an inkjet printer that reproduces a digital image with ink and paper, a 3D printer takes virtual data that are derived from cross-sectional

Acad Radiol 2016; ■:■■–■■

From the Department of Radiology, George Washington University Hospital, 900 23rd St. NW, Suite G2092, Washington, D C 20037. Received March 22, 2016; revised April 23, 2016; accepted April 26, 2016. **Address correspondence to:** R.J. e-mail: rjavan@mfa.gwu.edu

http://dx.doi.org/10.1016/j.acra.2016.04.010

imaging. The anatomic data are then processed by 3D reconstruction software into a virtual 3D mesh. Various materials are then loaded onto 3D printers to fabricate solid forms in a layer-by-layer fashion. The exquisite and customizable detail can be produced in a reasonable time frame and at a relatively low cost. Innovations in 3D printing have the potential to afford the medical team direct production capabilities and advance the practice of medicine through unique and customizable educational tools.

The visualization of anatomy is historically limited to flat computer screens or cadavers (2,10). Advanced segmentation techniques improved visualization at workstations, but 3D virtual images never provided hands-on experience that would translate to a direct understanding of anatomy for both the radiologist and medical team. This limitation has been overcome with the advent of 3D printing. Industry and academia made improvements in 3D printing in process efficiency and with user-friendly online commercial services. Customizable products are now available with desktop 3D printers at a relatively cheap cost. As 3D printing scales up, there is an expected decrease in manufacturing costs, making 3D printing and customized educational tools more accessible to the medical community and public.

Many industries use 3D printing such as manufacturing, metallurgy, aeronautics, and the automotive industry (2,10). These products are manufactured with numerous materials, such as metals, plastics, nylon, sandstone, wax, porcelain, and other composite materials. However, 3D prints from the medical industry are typically limited to resins, thermoplastics, and photopolymers because of 3D complexity of anatomy leading to constraints in manufacturing and at other times the use of multiple materials. Materials science, big data, and computational modeling are promising fields to improve 3D models (2,11,12). As 3D models better approximate the physical properties and fluid dynamics of biological systems, there is added value to simulation centers and medical education that benefits both the patient and medical providers.

Radiologists can take on a leadership role in providing value-based patient care, contribute to the movement toward precision medicine and advance medical education techniques. This article highlights how radiologists may use low-cost 3D models to reach this end and to enhance their presence among patients, physicians, medical students, and trainees across all specialties. We printed the complex segmental anatomy of the liver, lung, and prostate as well as branch anatomy of the coronary arteries and the Circle of Willis as examples to demonstrate the potential of custom 3D printing in enhancing medical and patient education. A multitude of techniques were implemented and are described, therefore allowing individuals with various levels of technical expertise and resources to maximize their ability to create their desired custom educational tools.

MATERIALS AND METHODS

There are two fundamental methods for preparing digital 3D models for printing. The virtual 3D model can be the result of work purely within graphic design software, or alternatively it can be 3D reconstructed from cross-sectional imaging. These methods can also be combined for hybrid results. The initial graphically designed model can be obtained commercially, via shared online libraries, or designed by an artist or engineer, and the subsequent modification can be performed either by a graphic designer or by the radiologist. In this report, we demonstrate an example of each of the aforementioned methods and their combinations (Table 1).

The lung model (Fig 1) is an example where the initial digital 3D mesh is graphically designed and is obtained from online library at no cost (3DCADBrowser.com). Modifications were done using a free version of Autodesk 3D Studio Max with a student/educator license allowing for the addition of the main pulmonary arteries to provide the connection between each lung, as well as to create a surface color map representing the lobes and segments of the lungs. Polyamide material was used for simplicity and durability. Coloring was performed after 3D printing with readily available marker pens along with wax plaster material, commonly known as crayons. Spray-painting provides an additional method that creates a more homogeneous result.

The liver model (Fig 2) required the most work for developing the initial 3D mesh due to the intricate relationship between the vasculature as the source of the actual anatomic segmentation methodology of the liver. Initial two-dimensional (2D) diagrams were hand-drawn to communicate cut planes of the liver with a graphic designer, whose services were available as a freelance artist for a fee through a reputable online source (FlatPyramid.com). Multiple instances of corrections and modifications had to be performed for achieving the final

TABLE 1. Combination of Methods for Creating Final Digital 3D File with Relative Time and Cost Involved, Where the Simplest Model, the Lung, Is Used as a Reference

Anatomy	Initial 3D Mesh	Method of Obtaining	Modification	Time	Cost
Lung	Graphically designed	Free online library	Radiologist	–	–
Liver	Graphically designed	Commercially customized	Graphic artist	+++	+++
Coronary	Graphically designed	Commercially available	Radiologist	+	++
COW	3D Reconstructed (MRA)	Performed with free software	Radiologist	++	+
Prostate	3D Reconstructed (MRI)	Freely available online	Radiologist	+++	++

COW, Circle of Willis, MRA, magnetic resonance angiography; MRI, magnetic resonance imaging.