Special Review

Clinical Applications of 3D Printing: Primer for Radiologists

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Three-dimensional (3D) printing refers to a number of manufacturing technologies that create physical models from digital information. Radiology is poised to advance the application of 3D printing in health care because our specialty has an established history of acquiring and managing the digital information needed to create such models. The 3D Printing Task Force of the Radiology Research Alliance presents a review of the clinical applications of this burgeoning technology, with a focus on the opportunities for radiology. Topics include uses for treatment planning, medical education, and procedural simulation, as well as patient education. Challenges for creating custom implantable devices including financial and regulatory processes for clinical application are reviewed. Precedent procedures that may translate to this new technology are discussed. The task force identifies research opportunities needed to document the value of 3D printing as it relates to patient care.

Key Words: 3D printing; three-dimensional printing; personalized medicine; additive manufacturing; radiology; preoperative planning.

INTRODUCTION

What began as a largely industrial tool to facilitate concept-to-prototype development, three-dimensional (3D) printing has evolved into a widely used technology, affecting many aspects of modern society. The term "3D printing" grew out of the research and development laboratories of the automotive and aerospace industries (1). The technology was developed throughout the 1980s and 1990s (2–5), and medical applications were initially reported in the early 2000s (6–9). Initially, these reports focused on custom prostheses (6,7), but as the technology improved, reports of using anatomic models for preoperative planning began appearing (10–13). Today, 3D printing continues to find new applications: customized eyeglasses can be printed to exact specifications (14), an increasing number of foods can be printed on demand (15), and there are plans to manufacture cars entirely using 3D printing (16).

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Recent rapid growth of 3D printing in medicine has been staggering. A search of Pubmed.gov using the term "3D printing" yielded only six publications in the year 2000, 61 publications in 2010, and more than 1100 publications in 2016. To encourage continued growth of this technology, the National Additive Manufacturing Innovation Institute was launched in 2012 (17). Many professional societies have also advocated the use of this technology in medicine. For example, the Society for Manufacturing Engineers has a dedicated medical 3D printing workgroup (18). In 2016, the Radiological Society of North America formed the 3D Printing Special Interest Group. The 3D Printing Special Interest Group has already sponsored many educational sessions at the annual meeting and is committed to building evidence for clinical utility of 3D printing (19).

Undoubtedly, this topic has gained popularity because of the tremendous potential it offers to radiologists, our colleagues, and patients. If implemented correctly, 3D printing promises to improve patient care and enhance the relative contribution to that care by radiologists. Specifically, 3D printing can deliver personalized medicine based on the anatomic data radiologists acquire and interpret every day. Providing such a service offers a new way to interact with referring clinicians and a potential way radiology can demonstrate value in patient care.

Radiologists have witnessed the evolution of medical imaging that allows for 3D printing. Multiplanar imaging with computed tomography (CT) and magnetic resonance imaging gave rise to 3D reconstructions that improved the evaluation of complex anatomy (20–22). At its most basic level, 3D printing takes imaging data from the two dimensions of a computer screen to the three dimensions of the real world (22).

3D printing has been used in a wide range of healthcare settings including Cardiology (23), Cardiothoracic Surgery (24),

Critical Care (25), Gastroenterology (26), General Surgery (27), Interventional Radiology (28), Neurosurgery (29,30), Ophthalmology (31), Oral and Maxillofacial Surgery (32,33), Orthopedic Surgery (34), Otolaryngology (35,36), Plastic Surgery (37), Podiatry (38), Pulmonology (39), Radiation Oncology (40), Transplant Surgery (41), Urology (42), and Vascular Surgery (43).

The most immediate clinical applications of 3D printing are for presurgical planning, intraoperative guidance, and the production of custom implants. Increasingly, 3D-printed models are also used for educating physicians, trainees, and patients. However, clinical implementation of 3D printing has already faced important challenges, including financial, regulatory, and medicolegal restrictions. Discussed in subsequent sections, 3D printing has faced some challenges including lack of reimbursement as well as the initial time, cost, and personnel required to start a medical 3D printing laboratory. As advances in 3D printing continue to change health-care delivery, what role will the radiology community play?

This article by the 3D Printing Task Force of the Radiology Research Alliance reviews current issues related to the clinical application of 3D printing and their implications for radiologists. Specific topics include treatment planning using 3D printing, customized prostheses, bioprinting, 3D printing for medical and patient education, challenges to the clinical application of 3D printing, and opportunities for radiologists.

As more surgeons employ 3D printing technologies for treatment planning, it is important for radiologists to learn about the field and stay abreast of advancements. Because radiologists are responsible for proper image acquisition and interpretation of medical images, which are used to generate 3D-printed models, radiologists have an opportunity to take the lead in this emerging field and through 3D printing can participate more directly in operative planning and patient care.

Transforming Clinical Care

Treatment Planning

Treatment planning is a multistep process where clinical and imaging information is integrated to determine the best therapeutic options while saving operative time. With 3D printing, this can be creation of haptic models to plan the surgical approach along with cross-sectional imaging or, alternatively, creating custom prosthetics based on patient-specific anatomy. For more than a decade, additive manufacturing techniques have been used to improve surgical planning. Orthopedic, Maxillofacial, and Cardiothoracic surgeons were among the first to use 3D printing techniques to design custom prosthetics (25,33,34).

Why are 3D models of patient-specific anatomy so useful for operative planning? Perhaps the most obvious answer is that the models provide surgeons with an opportunity to understand the complex anatomy unique to each case in the dimension they will be operating in (28) (Fig 1). These 3D-printed anatomic models based on patient-specific anatomy can be used for surgical planning both in and out of the operating room (44). The use of 3D printing for treatment planning is subsequently discussed in three sections: Fracture Fixation, Resection of Renal Tumors, and Cardiovascular Applications.

Fracture fixation.—The use of 3D-printed models for operative planning has been implemented in a number of orthopedic and fracture fixation applications (34,45) (Fig 2). For example, Mao et al. (46) used 3D models in 22 patients with hip arthroplasty requiring revision surgery. The 3D models were used to fit the surgically altered acetabulum with commercially available cages or custom acetabular cages.

Chung et al. (47) used 3D-printed calcaneal models in patients with intra-articular fractures to plan internal fixation and

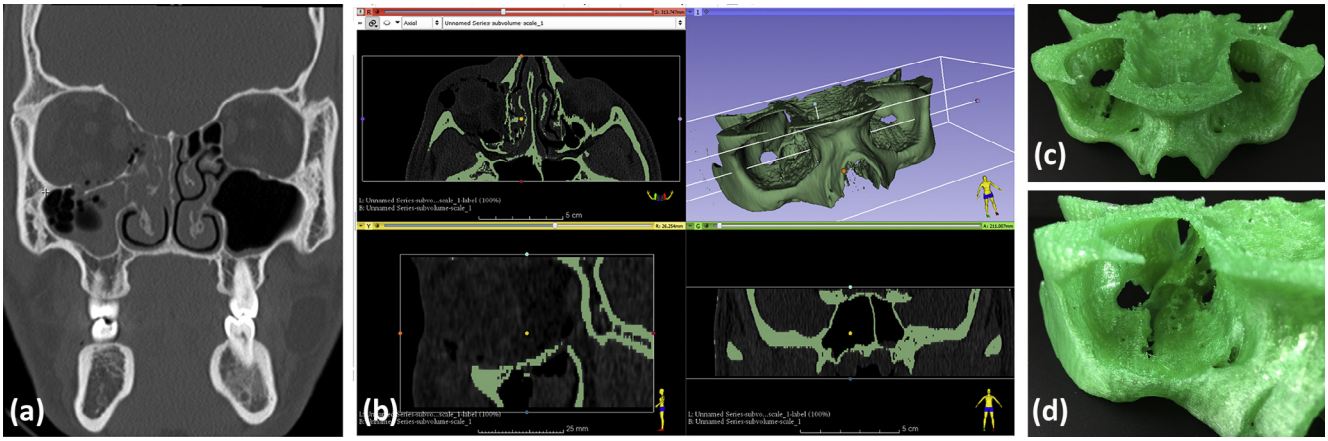

Figure 1. Three-dimensional (3D)-printed model of a right orbital blowout fracture. 22-year-old man following an altercation. **(a)** Coronal reconstructions computed tomography (CT) image of the facial bones, which shows a right orbital blowout fracture involving the medial and inferior walls. **(b)** CT DICOM data used to create a stereolithography (STL) file (3D Slicer version 4.6, www.slicer.org). **(c)** 3D-printed anatomic model of both orbits. **(d)** Photograph of the right orbit, which delineates the nature of the blowout fracture.