Individualizing Management of Complex Esophageal Pathology Using Three-Dimensional Printed Models

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Purpose. **In complex esophageal cases, conventional two-dimensional imaging is limited in demonstrating anatomic relationships. We describe the utility of three-dimensional (3D) printed models for complex patients to individualize care.**

Description. **Oral effervescent agents, with positive enteric contrast, distended the esophagus during computed tomography (CT) scanning to facilitate segmentation during post-processing. The CT data were segmented, converted into a stereolithography file, and printed using photopolymer materials.**

Evaluation. **In 1 patient with a left pneumonectomy, aortic bypass, and esophageal diversion, 3D printing enabled visualization of the native esophagus and facilitated endoscopic mucosal resection, followed by hiatal dissection and division of the gastroesophageal junction as treatment. In a second patient, 3D printing allowed enhanced visualization of multiple esophageal diverticula, allowing for optimization of the surgical approach.**

Conclusions. **Printing of 3D anatomic models in patients with complex esophageal pathology facilitates planning the optimal surgical approach and anticipating potential difficulties for the multidisciplinary team. These models are invaluable for patient education.**

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The first description of three-dimensional (3D) printing was in 1982 by Hideo Kodama of Nagoya Municipal Industrial Research Institute, although the first 3D printer was only manufactured 10 years later. Recently, the surgical applications of this technology have expanded. Three-dimensional technologies can be used to tailor the operative strategy to each patient's pathology and anatomy. This becomes particularly relevant if the patient has a complex anatomy due to underlying pathology, native anatomic anomalies, or prior surgical intervention. The 3D modeling provides the surgeon an opportunity to rehearse the procedure, to prepare, and to problem solve before the patient enters the operating room. Tangible 3D models also aid in preoperative discussion between multiple surgical specialists. The 3D printing or rapid prototyping has already been utilized to plan operative interventions in a number of specialties [1–5] and to develop a scaffold for biologic grafts when required [6–10]. These models are invaluable for preoperative education of the patient and family members allowing for a more informed consent process. We describe the unique application of a technique to enhance esophageal 3D modeling, and describe our application of 3D printing to complex esophageal cases.

Technology

Overview

Our institution has utilized 3D printing since 2006, with over 160 models produced. For patients with complex esophageal pathology, we have used the unique application of an oral effervescent agent in combination with a positive enteric contrast agent to distend the esophageal lumen during computed tomography (CT) scanning. This facilitates differentiation of the esophagus from adjacent mediastinal structures for segmentation purposes. Segmentation is the process of accurately separating and color coding critical anatomic structures within a cross-sectional imaging data set in order to optimize visualization and display. The diagnostic problem in defining esophageal anatomy is the esophagus is naturally collapsed, and the wall is of soft tissue attenuation and identical to surrounding mediastinal structures. Distension of the esophageal wall using air and positive contrast facilitates rapid identification of the contour from surrounding structures given the large differences

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in CT attenuation. The better-visualized esophageal wall facilitates segmentation in relation to other mediastinal structures, rendering a more accurate 3D printed model.

Technique

Patient Preparation

A positive enteric contrast agent is given prior to effervescent granules. Positive contrast agents used in our practice include an iso-osmotic iodinated agent diluted with water for postoperative patients (Omnipaque 300; GE Healthcare; Cork, Ireland; 15 cc added to 500 cc water) or barium sulfate suspension for preoperative patients (Berry Smoothie Readi-Cat 2; barium sulfate suspension 2.1% weight per volume; EZ-EM, Inc, Lake Success, NY). We then give effervescent granules containing sodium bicarbonate (E-Z-GAS II; EZ-EM, Inc) to release carbon dioxide within the esophagus. The effervescent granules are mixed with 20 cc water and swallowed or injected through a tube if the patient cannot swallow. After the patient is placed in the decubitus position, several more swallows or injections of positive enteric contrast agent are given to fill a redundant or patulous esophagus.

Image Acquisition

Images are generally acquired in 2 positions using automatic exposure control to ensure similar image noise across the acquired volume. Standard low-dose techniques such as kV selection, automatic exposure control, and iterative reconstruction are used to create high contrast differences between the esophageal wall, air, periesophageal fat, and positive enteric contrast. Routine multiplanar images are obtained. From these data additional thin 1-mm images are reconstructed in order to minimize stair-step artifacts in 3D printing.

Image Segmentation, Processing, and 3D Printing

The imaging data, stored in Digital Imaging and Communication in Medicine format, is imported into proprietary software (Materialise, Leuven, Belgium). The imaging data are segmented using Hounsfield units and hand segmented to provide greater accuracy. The segmented data are converted into a virtual 3D anatomic model (Fig 1A) and exported into a STereoLithography (STL) file. The final STL file was re-imported into the source imaging data to ensure the outline matches initial segmentation.

The STL files were imported into Mimics software (Materialise) for printing (Objet350 Connex multimaterial; Stratasys, Eden Prairie, MN). Using the 3D printing software, different colors were assigned to the anatomic structures and several materials, rigid and flexible, were selected. Life-size models were printed using liquid photopolymers on the PolyJet 3D printer (Stratasys). The material was printed with surrounding support material (Fig 1B) which was washed off (Fig 1C). These life-size anatomic models (Fig 1D) were used for multidisciplinary preoperative discussions, surgical planning, and for patient education.

Clinical Experience

Case 1

A 41-year-old gentleman, status post-bilateral orchidectomy and chemotherapy for testicular teratomas developed mediastinal lymph node involvement necessitating mediastinal lymphadenectomy. Subsequent involvement of aortopulmonary window nodes and adventitia of the descending thoracic aorta led to a left pneumonectomy and descending aorta reconstruction using a 20-mm Dacron graft. All margins were negative at this resection. His postoperative course was complicated by an aortoesophageal fistula, necessitating emergent endovascular stent placement and left thoracotomy, drainage of empyema, cervical esophagostomy, and gastrostomy (percutaneous endoscopic gastrostomy; PEG) tube placement. Due to persistent sepsis and hemoptysis he underwent an ascending aorta to descending aorta bypass with a 60-mm Dacron graft under circulatory arrest. The proximal descending aorta was debrided, the infected graft resected, and the aorta oversewn using a flap technique. The esophagus was subsequently repaired primarily, diverted proximally, and reinforced with a serratus anterior muscle flap distally in conjunction with a thoracoplasty to limit the remaining space. After these surgeries, he presented to our institution with concern for repeated septic episodes related to the proximity of his defunctionalized thoracic esophagus, persistently leaking around his descending aorta with risk of recurrent fistulization. He underwent retrograde endoscopy through his PEG site to assess the proximal extent of esophagus in addition to bronchoscopy and fluoroscopic evaluation of his remnant esophagus. He then underwent multistep imaging procedures to obtain strategic imaging data needed to translate into a 3D model. After fluoroscopic placement of a catheter within the lower esophagus through the patient's PEG site a chest CT was performed. Positive oral contrast and air was hand injected through the catheter prior to intravenous contrast administration and CT scanning. This resulted in enhancement of vascular structures and an air- and contrast-filled distended distal esophagus (Fig 2A). From these data, the spine and ribs, esophagus and fistulous tract, spit fistula, stomach, aorta, aortic graft, trachea, veins, and diaphragmatic crus were segmented and color coded (Fig 2B). This was converted into a virtual 3D model (Fig 2C) and a life-size anatomic model was printed (Fig 2D).

Printing a 3D model enabled a hybrid endoscopic-surgical management approach, which would have otherwise not been possible. We were able to use the model to simulate our surgery preoperatively and to measure and plan the safe extent of the endomucosal resection (EMR). This was facilitated by visualizing the proximity of the esophagus to the graft. The model was invaluable intraoperatively and enabled real-time