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REVIEW

A brief introduction to medical image processing, designing and 3D printing for orthopedic surgeons

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ABSTRACT

Advancements in technology and the industry have changed the way that physicians deliver healthcare to their patients. Orthopedic surgery is one of the medical fields chasing advancing technology closely and making it a part of routine practice quickly. Patient-centric approach and customization of the care according to patient's needs are the key components in this new concept. Customized surgical planning with three-dimensional (3D) modelling and printing of the anatomy of each patient scheduled for surgery, custom made implants are on their ways to become the standard of the care. As a result, a higher proportion of technical personnel than before is expected to be involved in the healthcare. Orthopedic surgeons need to be familiar with this new working model and technical terminology to be able to communicate with the technical members of healthcare thoroughly. Processing of the medical images, computer-aided design (CAD) programs and 3D printing are the crucial parts of this workflow. In this review, we discuss the basics concepts of these components with the examples from 3D Slicer as a medical image processing platform and Shapr3D as a CAD platform, with the aspect of orthopedic surgeons.

Keywords: DICOM, image processing, industry 5.0, printing, stereolithography, three-dimensional.

Orthopedic surgery is one of the medical fields that rapidly adapts and utilizes advancing technology and highly effected by the industrial revolutions historically. Beginning in the mid-19th century, from steam generated mechanical manufacturing of surgical equipment to mass production of implants, diagnostic devices based on X-ray and electromagnetism currently, there are many remarkable examples for the enlightenment of the orthopedic surgery with the advancements in the industrial techniques.[1]

In the beginning of the new millennia, digitalization penetrated almost every step of healthcare with the Industry 4.0 and it has already had many settled applications in the field of surgery. Introduction of the Industry 5.0 concept in 2015, brought out the ideas of greater involvement of human intelligence in the manufacturing process and personalization of end products.[2] Those ideas reflected to healthcare services, particularly to surgical fields as further patient centric approach than ever before, such as customization of implant production and personalized surgical planning.

Patient-centric approach and customized services and products requires interdisciplinary collaboration between the orthopedic surgeons and technical members of healthcare team, such as technicians, engineers, and product designers. To adapt this new health service model, both parties need to be able to speak each other's languages, more than ever now.

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In this review, we address two categories of computer programs that an orthopedic surgeon should be familiar with to be able to communicate with technical members of the team. The first one is about processing medical images and the latter one is designing custom made implants or surgical instruments.

MEDICAL IMAGE PROCESSING

Three-dimensional anatomical modelling in virtual environment and most of the time printing this 3D model physically is a highly productive way of analyzing patient's anatomy and planning the surgery or conservative treatment.[3,4] There are several steps for obtaining the 3D or computer-aided design (CAD) model of a particular anatomical region including image acquisition with computed tomography (CT) or magnetic resonance imaging (MRI), obtaining the image data in Digital Imaging and Communications in Medicine (DICOM) file format, segmentation, surface rendering with mesh formation and transformation to a CAD file format; most commonly "stl".

Since the first two steps are readily performed at most healthcare clinics by the radiology technicians in routine basis; segmentation, rendering and obtaining the stl file are the crucial steps an orthopedic surgeon should be familiar with.[5] To perform those steps a medical image processing software is required. There are many paid software in the market, as well as the ones with free license of use. Mimics Innovation Suite (Materialise Inc.), Invesalius (Renato Archer Information Technology Center), Vesalius3D (PS-Medtech), ITK-SNAP (ITK-SNAP), Seg3D (University of Utah), OsiriX (Pixmeo SARL) and 3D Slicer (3D Slicer Community) are some of the examples. Among them authors' preferred software is 3D slicer which is a free open-source licensed platform for medical image processing, segmentation, and 3D visualization.[6] It was created as a byproduct of a master's thesis with the collaboration between Surgical Planning Laboratory at the Brigham and Women's Hospital which is an affiliate of Harvard Medical School and the Massachusetts Institute of Technology Artificial Intelligence Laboratory in 1998 and is being upgraded continuously by an international community of scientists under the roof of 3D Slicer Community.[7,8] The software has many modules meeting the required tools for each step of 3D modelling. Thanks to BSD-style open-source license it has, researchers are allowed to add new methods, algorithms, and tools they developed in the form of Python software package modules and combine them with the built-in features of 3D Slicer.

Segmentation is the first step for processing medical images. It can be defined as isolation and extraction of the imaging data that belongs to anatomical structure of one's interested. For orthopedic surgery, this commonly means removing out soft tissues and isolating bones. Segmentation can be done either manually or automated. Since most of the time a set of cross-sectional DICOM images belonging to the region of an orthopedic surgeon's interest contains hundreds of slices, using the automation first, then editing manually, if necessary, is the reasonable choice.

In automated segmentation, region of interest is delineated according to certain algorithms which can be found in the "Segment editor" module of 3D Slicer. One of the most useful algorithms for segmenting bone is thresholding, due to high-contrast differential of bone with respect to soft tissues. In thresholding, user defines a range of density in the form of Hounsfield Unit (HU) for the software to highlight the voxels within that range. Although the density of the bone is between +152 and +1,000 HU in general, this range may change according to region of the bone (cortical/cancellous), mineral density of the bone (local or generalized osteopenia) and age of the patient (lower in children due to incomplete mineralization).[9]

'Grow from ceeds' is another powerful tool of 3D Slicer. It relies on the principle that densities of the neighboring voxels belonging to the same tissue must be comparable to each other and relatively discrete from the tissue's voxels' next to it. This algorithm compares the HU of each voxel with the one's next to it, in case there is no significant difference the software considers them to be part of the same tissue or anatomical structure and highlights that tissue till the edges until detecting a dramatic change in density.

Thresholding and 'grow from ceeds' tools generate a rough outline for the structures interested. In case of a need for further detail in model, other tools such as 'island effect', 'level tracer', scissor, eraser or manual segmentation can be used for fine adjustments.

Once the segmentation is completed satisfactorily, the segmented (or highlighted) voxels need to be gathered in the form of a mesh composed of triangles and other polygons of voxels. This process is termed as tessellation and the mesh composition produced with tessellation process composes the 3D surface model (or CAD model) of the anatomical structure to be worked on. An example of 3D model of the bones of a right cadaver shoulder can be seen in Figure 1

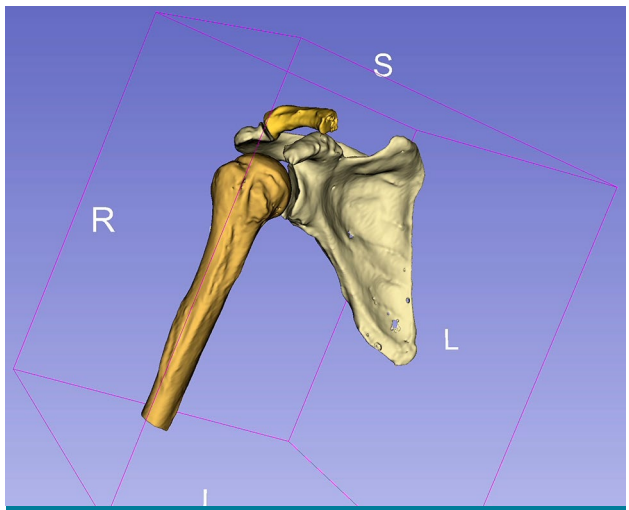
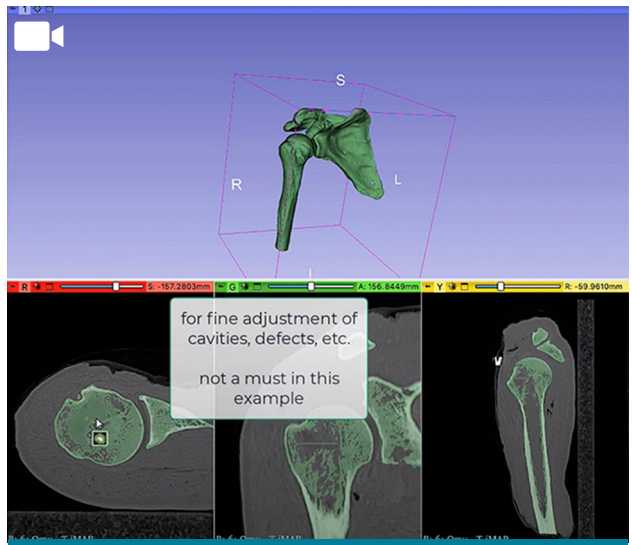


FIGURE 1. 3D model of the bones of a cadaver shoulder generated with 3D Slicer application.



VIDEO 1. Segmentation of the bones of a cadaver's right shoulder using 3D Slicer application.

and the video demonstrating the segmentation of it is available through the link (Video 1).

The most commonly used CAD file format for 3D printing is 'stl' which stands for Standard Triangle Language or Standard Tessellation Language. One important issue to know about the stl format is that the data in it only represents the geometrical shape of the object, not the texture or surface color. To include and transport the information about texture, color or any other common CAD model attributes within a solitary file, one must use obj file format.[5] The 3D Slicer supports exporting 3D models with both of those file formats.

The mesh file exported from the CAD program is not printer ready most of the time. Mesh editing and slicing processes must be performed to get the file ready to be recognized and worked on by the 3D printer seamlessly. This part of the workflow can be referred to an engineer or technologist. However, if we need to mention briefly about the processes, mesh editing is done to fix the defects in the polygon system in representing the real-world 3D objects such as polygons intersecting each other or gaps between them. There are many open-source programs such as Blender (The Blender Foundation) offering powerful tools to fix the mesh errors and 3D Slicer includes several built-in mesh editing features, as well. Slicing is the process of converting a 3D model into a set of two-dimensional (2D) slices so that printer build it layer by layer, usually with a thickness of 0.1 mm. Slicer applications are usually offered by the manufacturer of the 3D printers specific to the product.

The 3D printers can be classified according to type of raw material used (thermoplastic polymers like polylactic acid [PLA] or polyethylene terephthalate [PET], photosensitive resins, metals like titanium or steel, ceramics) or manufacturing techniques (fused deposition modelling [FDM], stereolithography [SLA], powder bed fusion).[10] Polylactic acid with fused deposition technique may be eligible for quick and low-cost modelling of anatomical parts. To obtain finer details as in the case of a surgical guide or a surgical tool prototyping, using biocompatible photosensitive resins with SLA technique is recommended.[11] Steel or titanium alloys such as Ti64 can be preferred for the manufacturing of custom made implants or reusable surgical equipment.[12]

CAD PROGRAMS FOR PARAMETRIC DESIGN

The other category of programs to be mentioned about is CAD programs that allows parametric design of custom-made implants or surgical equipment. There are many software available AutoCAD (Autodesk), Rhinoceros (Robert McNeel & Ass.), Cobalt (Ashlar-Vellum) or Shapr3D (Siemens PLM Components). The authors prefer Shapr3D application which has a subscription-based license with free educational license for academics.[13] The software works on Windows, MacOS, and iPadOS platforms. A very comprehensive built-in video tutorial series and the user interface compatibility with electronic pencils make it a great alternative for the ones completely unfamiliar to CAD programs and parametric design.

In conclusion, the healthcare industry always followed the changes in the way industry works. Orthopedics had always been one of the pioneer branches of medicine in adopting the advancements in technology and industry. In the new era of this human-centric medical services, orthopedic surgeons should be keeping themselves up to date and be ready for both using technology and being a developer of it.

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