MRI versus CT as Image Data Source for 3D Printing Bone

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In orthopedics, 3D printing is a novel way of visualizing dense human tissue and structures, for example bones and ligaments, but also the respective relations between them, thus providing the surgical team with taking the preoperative planning of an intervention one step further from 3D computer reconstructions. In order for a medical 3D print reconstruction to be possible, bidimensional imaging is necessary, in the form of DICOM files. These are then used by specific software in order to create an STL file, that can then be inputted into a 3D printer and a three-dimensional replica of the desired structure, usually on a 1:1 scale, can be generated. We aim to compare two methods of acquiring and processing of 2D images – MRI and CT scans – as sources of DICOM files, with the end purpose of 3D printing the image of human bone.

Keywords:MRI, CT, 3D printing, bone, ligament, artery, pre-op planning.

Orthopedic surgery is specialty heavily relying on visual data, both in the operative field as well as before the Operating Room, in planning the surgical act. More and more so, the preoperative planning stage is becoming increasingly important to the success of a surgery, especially with the development of individualized templates for each patient [1]. With the ever more complex development of computer software and hardware [2], imaging modalities are also becoming more and more refined, and an increasing volume of work is being done in the area of integrating various engineering concepts into applied medicine, like 3d printing [3] with bioresorbable or unresorbable materials [4], both for relatively small defects with cancellous-type scafflod structure [5], as well as for large defects or endoprosthesis [6] and even limb amputation and exoprosthetics [7]. 3D printing of scaffold-like structures based on computer imaging of a bony defect has been widely described [8, 10, 11], possibly followed by patient-derived cell seeding [12].

MRI, either with contrast or without, is widely used in orthopedic surgery as a source of information regarding mostly soft tissue: menisci, ligaments, capsule, muscles, blood vessels and nerves. In a clinical context, it is more often used in a chronic setting to explore for example tumors [13] or soft tissue articular lesions (labral lesions, cartilage lesions, menisci and ligaments) [14].

CT is also a much-used imagistic means, especially in trauma, where the speed of execution and precision in rendering bony surfaces make it a very useful tool for the orthopedic surgeon, especially when the images are used to recreate a 3D replica of the area in question [15]. It is also useful in evaluating bone tumors, both preoperatively and as a means of follow-up, despite the cumulative irradiation [16, 17].

Experimental part

Materials and methods

It is well known that bone structures as well as some soft tissue structures (ligaments, arteries, etc) can be 3D printed, and that the quality of the image is directly dependant on the quality and quantity (number of slices) of the medical imaging data that is being used, and also on the processing capabilities of the computer software.

We present an analysis of the technological means by which MRI scans and CT scans are produced, from the point of view of the creation of a 3D print-out of a human organ or tissue structure.

In MRI as well as in CT we do not acquire precisely bidimensional (2D) images, but slices that have also thickness. In fact, we obtain voxels instead of pixels.

The way we acquire a 2D image of an organ or tissue, in order to 3D print it, is different in MRI and CT scan procedures.

In MRI, the image is generated by the net transverse magnetization vector of the hydrogen protons of the sample translated in a variable electrical signal. The signal intensity (SI) is directly proportional with the net magnetization and produces lighter or darker areas in the 2D image. The net magnetization of the hydrogen protons is obtained applying two exterior magnetic fields (one static and longitudinal, B_0, and the other one oscillating, in order to produce the magnetic resonance effect, and transverse, B_1).Also, in order to measure the signal from the area of interest, gradient magnetic fields, *G*, are used. The static and longitudinal magnetic field is always on, only the transverse magnetic field generated by radio frequency pulse is turned off after a certain period of time in order to measure T_1 and T_2, two time constants, closely related with the longitudinal magnetization relaxation and, respectively, with transverse magnetization relaxation. As the transverse magnetization decreases exponentially in time and longitudinal magnetization increases from 0 to the initial value after the radio frequency pulse is turned off, T_2 is the time needed for transverse magnetization to decrease such that we lose 30% of the initial signal intensity and $T_1$is the time needed such that we regain 63% of the initial longitudinal magnetization. $T_1$and T_2 are specific to each tissue.

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The signal intensity depends in fact of four parameters: proton density, time relaxation T_1, time relaxation T_2 and flow. However, the signal we can detect is not constant, but decreases exponentially. The 2D image we obtain is a map of the signal intensity of the sample or of the area of interest. The contrast of the image is obtained manipulating other two important parameters, namely the repetition time T_R and the echo time T_E.

The T_R is the time between consecutive 90 degree RF pulse and T_E is the time when we choose to measure the echo (the signal from the transverse magnetization component which decreases over time). Changing these parameters we can dramatically change the contrast of the 2D image.This is why in MRI the same tissue can be brighter in some images and darker in others, depending on the values we choose for T_E and T_R.

In CT, one slice of sample or area of interest is divided into voxels and each voxel has a number assigned which represents the absorption of X-rays as it passes through that particular small part. In simple terms, the numbers are translated in shades of gray and that is how the 2D image is produced. The Hounsfield unit (HU) is used to calibrate the CT scanner in order to always obtain the HU of water equal to 0. For example, cortical bone has +3000 HU, while cancellous bone has +700 HU.

As an image has approximately 4000 shades of gray, display monitors have 256 shades of gray and human eye can see 30-90 shades of gray, we can be sure the correct 60 shades of gray are properly appreciated by adjusting the *window width* and *level*. The *width* affects the contrast scale. If the *window width* is narrow we have a high contrast in the image. For the *level* we should choose the HU of the object of interest (bone, for example).

We compare MRI and CT scans using several key factors, such as: image processing capacity using segmentation and volume rendering techniques in order to obtain the 3D surface to be printed, the capacity to optimize the surgical time as a patient-advantage factor, and last but not least the amount of radiation that the patient would be subjected to in order to obtain the image data.

Creating a 3D print-out of bone means, first of all, converting into a STL file a collection of 2D cross sectional images obtained in the DICOM format either by CT or MRI scan procedure (figs. 1, 2). STL file is the format that almost any 3D-printer can use. The conversion process can be made using software such as 3D-Slicer, Mimics, Osirix and others.

Fig. 1. Knee bones (distal femur, proximal tibia and patella) from MRI scan capture

Fig. 2. Knee bones (distal femur, proximal tibia and patella) from CT scan capture

The 2D-image acquired using a CT/MRI scan should undergo two phases: segmentation and volume rendering in order to obtain the STL file.

Segmentation

There are many segmentation techniques that can be applied such as thresholding-based segmentation [18], edge detection [19], region growing [20]or model-based techniques[21]. Almost all of these segmentation techniques can be applied manually or automated. Of course, automated ways are desirable [22].

Concerning bone segmentation using thresholding-based technique, it is well known that many software will do this in automated manner for CT scan image (fig. 3) because they separate the components of the image according to intensity, in terms of the predefined CT numbers (Hounsfield unit) of structures from low HU structures such air (-1000 HU) to high HU structures such bone (3000 HU).

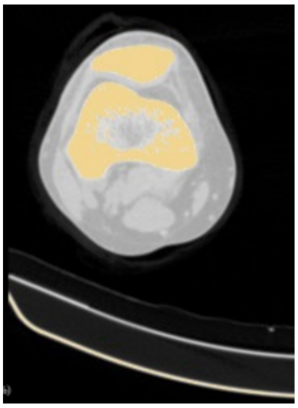

Fig. 4. Bone volume obtained from knee scan

As for MRI scan image, since there are no predefined pixel values such as CT numbers and overlap between adjacent tissues can often occur, bone segmentation using thresholding-based technique is somehow challenging. However, bone segmentation from MRI scan image using thresholding-based technique is much more easier rather by increasing signal intensity from bone (using ultrashort echo time T_E) or by minimizing soft tissue contrast to enhance bone-soft tissue boundary (using *Black Bone* MRI technique) [23].Good results were obtained with the *Black Bone MRI* technique (whose parameters are: T_E of 4.2 ms, T_R of 8.6ms, a flip angle of 5°, slice thickness of 2.4 mm, slice spacing of -1.2 mm, Scan FOV 24 cm, phase encode 256, frequency encode 256, receive bandwidth 31.25, ZIP 2512), although the segmentation is not always entirely automated.

Volume Rendering

As far as segmentation phase is well undergone, volume rendering phase does not add new challenges (fig. 4).

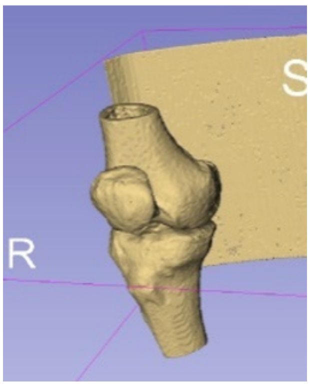

Fig. 3. Bone segmentation from knee scan.

Results and discussions

By analyzing the means through which 3D printable image files (STL files) are constructed from acquired MRI and/or CT file data (DICOM files) we come to better understand the protocols for image acquisition regarding the human organs and tissues that are involved in Orthopedic surgery: especially bone, but also ligaments, tendons, nerves and vessels, menisci, labrums and capsules, and thus make a better indication of whether MRI or CT scans should be performed in order to 3D print a replica of the desired organ. Using both MRI and CT scans we were able to produce acceptable 3D printed replicas of anatomic structures, such as bone, of comparable quality. First, we used CT and MRI scans with a reduced number of slices and through manual segmentation and/ or automatic segmentation(22) we obtained similar STL files, although not satisfactory for 3D printing. In order to improve our outcome we then used CT scans with increased number of slices. We obtained very good quality printable STL files (fig. 5.).

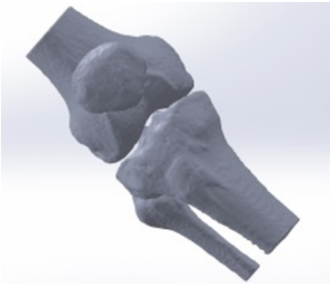

Fig. 5. STL file image ready for 3D printing

There are various methods to integrate 3D printing in the surgery of the knee described in the recent literature, keeping up with other recent developments in the field that further integrate technological progress with medical progress. For example, Wang et al. [24] have published the results of a study on 66 patients, from October 2013 to October 2015, in which they compared standard tumor resection technique to 3D printed surgical guides, for malignant bone tumor around the knee joint. Their research showed that while the operating time did not vary significantly, the blood loss, resection length and complication rate were *significantly lower* for the patients in the group where the 3D printed surgical guides were used; for the same group they found the postoperative evolution to be better.

Ni et al., in their 2018 study published in Arthroscopy [25], found that 3D printing can be used to improve the accuracy of bone tunnel placement in the reconstruction of the anterior cruciate ligament. For this, they scanned 20 human cadaveric knees with thin-layer computed tomography (CT), installing customized bone anchors prior to data acquisition, and on the computer models of the knees they calibrated the size and direction of the tibial and femoral tunnels, according to reference point marked at the bony insertions of the ACL. They 3D printed resin templates that were used to drill the femoral and tibial tunnels in the cadaveric knees, that were then CT scanned and compared to the planned tunnels. The results found the tunnels to be closely matched.

Okoroha et al. [26] also used CT as a source of image data in order to generate a 3D printed, one-to-one scale replica of the distal femur of a patient, which was used to correctly size an allograft plug, with favorable intra operative and postoperative results.

On the other hand, Rankin et al. used MRI as a source of image data in their 2018 study [27] , where they used scans of the patients' uninjured contra lateral knee in order to identify the anatomic position of the ACL's femoral footprint, information that was then used through 3D computer design to create patient specific femoral tunnel guides. These were 3D printed and proved to be effective in determining the footprint of the femoral ACL insertion.

As we can see, although the literature is not vast, already examples of both CT and MRI as valid sources for image data with the aim of 3D printing bone have emerged, especially taking into account the rapid development of modern computing [28]. From a clinician's point of view, one must take into consideration the fact that a CT examination is routinely performed in trauma cases, whereas in a chronic case the possibility to perform an MRI of comparable value would prove useful by the lack of further irradiation for a patient that would probably already have been irradiated multiple times.

Conclusions

3D printing is an effective method of visualizing a wide array of human structures, be it organ or tissue, providing the surgical team with an innovative tool that ensures a better understanding of the surgical steps needed to complete a successful surgery, and it can be acquired from MRI scans as well as from CT scans, ensuring a much needed versatility as well as decreasing the overall irradiation of the patient.

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