Production of anatomical models via rapid prototyping

Eva Hnatkova, Petr Kratky and Zdenek Dvorak

Abstract **-** This work deals with the possibility of using two-dimensional medical image data acquired from computed tomography magnetic resonance imaging or ultrasonography for manufacturing of anatomical models via rapid prototyping. These realistic models can be utilised for surgical pre-operation planning or medical training. There is also a huge potential that in the future the customised implant produced via rapid prototyping would replace the currently used implants fabricated by conventional technologies as forging, machining and casting. This could bring the benefits such as the reduction of operating time, the faster patient recovery, no geometrical restrictions and better aesthetic and functional results. In this project the latest medical data processing software Mimics from Materialise was used to generate the three-dimensional models of spinae vertebrae which was adjusted with computer-aided design software Catia and converted into standard triangulated (STL) files. These highly accurate three-dimensional models of anatomical structures in STL format served to create realistic tissue models using rapid prototyping technology with Poly-Jet technology.

Keywords **–** 2D scans**,** medical imagining, medical segmentation, anatomical models, rapid prototyping, 3D printing

I. Introduction

RAPID prototyping, also known as three-dimensional (3D) printing, is a modern technological process allowing a quick fabrication of physical parts. The principle of RP is in the construction of the objects by additive layer manufacturing which is based on three-dimensional (3D) computer-aided-design (CAD) model [1,2]. It means that from the virtual 3D design is possible to generate physical models by building up layer by layer of the material [3,4].

Nowadays, there are various RP technologies available. The oldest method, which dates in the late1980s, is stereolithography that utilizes liquid photo-reactive polymer and ultraviolet laser to cure layer by layer. Then, the followed method was selective laser sintering (SLS) which employs electron beam to sinter the powdered material. Fused deposition modelling (FDM) is another method that involves extruding of material in small amount through a nozzle head. The nozzle heats firstly the material and after extrusion the material hardness immediately [5]. From the latest technologies is well known Multi-jet modelling, which uses a special jetting nozzle to build up the layers.

In medicine, RP offers the printing of various design features for preoperative planning or production of anatomical models which can be utilised for surgical training [6]. In the past, the fabrication of medical models was very difficult, because of the complex geometry of the anatomical structures. Prior to RP, anatomical models were manufactured using pressing, forging, machining and casting processes. But these processes were expensive and time-consuming [7,8].

In the coming years, RP has also an enormous potential to become the most convenient and reliable technique for direct manufacturing of custom-fitted implants or in tissue engineering [9-14]. The personalised implants with optimized design can provide benefits such as the reduction of operating time, the faster patient recovery, no geometrical restrictions and better aesthetic and functional results [15]. The appeal for the researchers is development of suitable biomaterials which can be processed via RP [16].

One of the important issues in RP applications in medical branch is how to obtain accurate 3D models of the required anatomical parts [17]. Normally, the imaging methods such as conventional radiographs, Computed Tomography (CT), Magnetic Resonance Imaging (MRI) or ultrasonography can be used for visualization of internal structures such as organs, bones or vessels.

The acquired CT, MRI or ultrasound scans in form of 2D slices can be than process using some medical image segmentation software to create the 3D visualization of internal tissues [18-20]. And after that, generate the 3D model which can be exported into the CAD software to correct the model prior to 3D printing or another option is to design a customised implant based on CAD anatomical model [21-22].

The aim of presented study is to show how helpful can be 3D printing in medical field and how can be converted 2D medical scan data from CT into 3D CAD models using a special software Mimics developed by Materialise and 3D CAD software Catia. Finally, two parts of spinae vertebrae will be printed using 3D printer based on Poly-jet technology.

II. Medical imaging

Medical imaging is a technique allowing the visualization of internal structures in the human body, such as organs, bones

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or vessels. The major methods include CT, MRI and ultrasonography.

A. Computed tomography (CT)

CT is a non-invasive medical imaging method that utilises X-ray technology to obtain detailed images of the tissues inside the body. Fig. 1 demonstrates the principle of CT scanning during an examination.

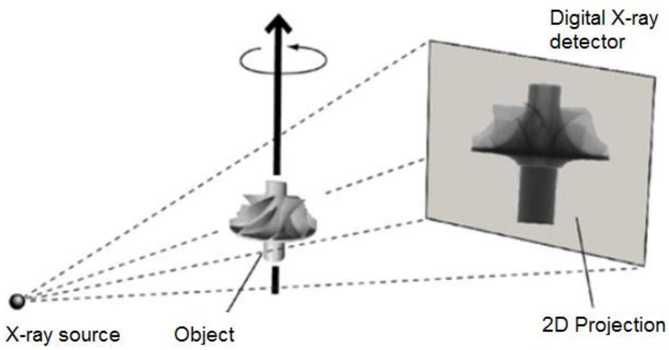

Fig. 1 Principle of CT scanning technology

As can be seen, the X-ray source rotates around the patient body and the object of interest absorb the radiation at different rates depending on tissue density. This allows the visualization of 2D projections on digital X-ray detector from variety of input angles. Then computer processes the X-ray views into cross-sectional images. A CT image is typically called "slice" which corresponds to certain thickness. The advantage of CT scanning is high quality images especially for hard tissue and this method is more tolerant to patient movement than MRI. On the other hand, the patient is exposed to radiation and there could be also potential allergic reaction.

B. Magnetic resonance imagining (MRI)

MRI uses radio waves and magnetic field to obtain medical scan data. The magnetic field reacts with the hydrogen molecules of the water within the human body and this reaction allows special software to generate an image. MRI is extremely useful in visualization of soft tissue and this method is without radiation exposure. Disadvantage is the intolerance of the body motion and of in vivo medical devices.

C. Ultrasonography

Ultrasonography is technique that utilizes high frequency sound waves (above 20 kHz) which easily penetrate fluids, but not solids. The ultrasound machine sends the sound waves into the human body and then is able to convert returning (echo) waves picked up by a sensor to generate a digital image. The resolution of the images produced by ultrasound tend to be grainy and mid to low resolution. Ultrasonography is a non-invasive procedure extensively used in gynecology, but the scans often exhibit some artefacts, which may affect a further segmentation.

III. Generation of Model Data

The extraction of 3D objects and its visualization is one of the most important steps in the analysis of the pre-processed medical image data. Among the most important medical imaging methods are CT and MRI, both of them produce 2D cross-sectional images, each of them representing a thin slice of the human body. Nowadays, the images are commonly available in the standard data format DICOM (Digital Imaging and Communications in Medicine) which retains 100% data quality and can be uploaded by many types of medical modalities [23].

A. Volume rendering

The volumetric data set in form of 2D images can be used for reconstruction of 3D virtual models that can be viewed from many directions. The typical medical image is composed of a 2D array of pixels each representing a unit area having some value of intensity. The intensities of pixels in medical imaging can be the radiation absorption in X-ray imagining, acoustic pressure in ultrasound or radio frequency signal amplitude in MRI.

For visualization of 2D image data as a 3D object may be used volume rendering. The images are usually acquired in a regular pattern and every slide has the same space between another, and also the number of pixels is the same. The 3D object is then built up out of the voxels which represents a unit of space. The colour of the voxels may be determined based on their gray value [24]. Volumetric rendering serves only for a volumetric visualization which is not supposed to any changes and for further work the data has to be adjusted in other software.

B. Medical image segmentation

Segmentation is the process of distinguishing objects in the data set from their surroundings so as to facilitate the creation of geometric models. There exist many of special biomedical software, which can processes 2D medical images from CT, MRI or ultrasound into 3D high accurate models of patient anatomy [25]. As an example, in Fig. 2 is shown the medical image segmentation in Mimics software developed by Materialse.

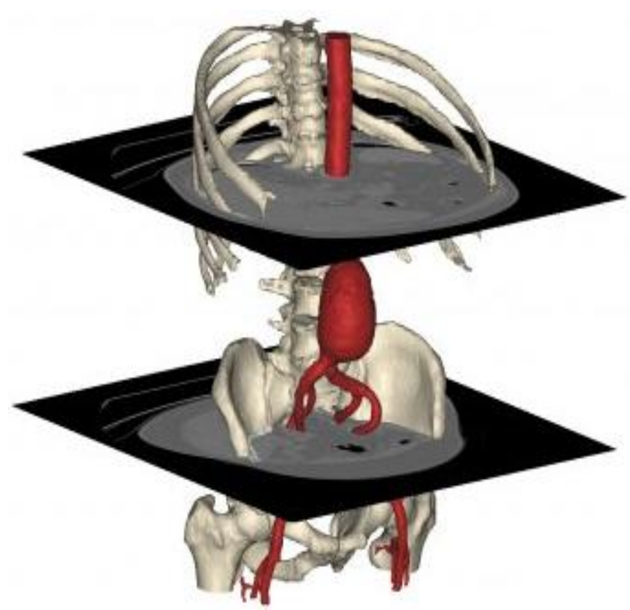

Fig. 2 Medical image segmentation in software Mimics [26]

The principle of medical image segmentation is generally based on thresholding which define an object by selecting a range of pixels gray values. Then the result is a set of segments that cover the entire image, or a set of contours extracted from the image. If it is applied to the whole volumetric data set of images, the resulting contours can be used to create 3D reconstructions with the help of interpolation algorithms [27].

Fig. 3 demonstrates an example of surface tracking, which is a reconstruction process for a geometric surface from volumetric data set.

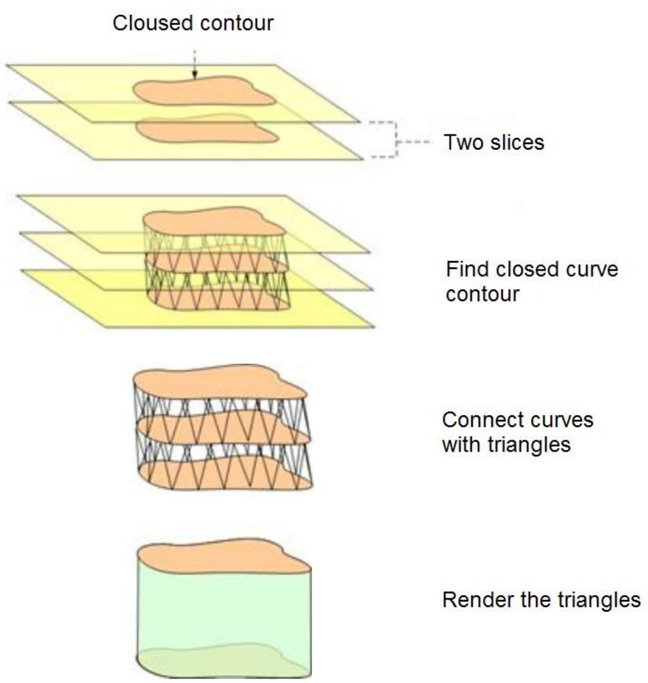

Fig. 3 Surface tracking by using a closed contour

Surface tracking is classified as indirect volume rendering, during which the data is transformed into a set of polygons representing the surface. The resulting geometric models are than useful for various applications as for further design of customised implants or for production of the physical anatomical models [28,29].

The quality of the input CT/MRI data and then the quality of the segmentation results are mostly affected by:

- Resolution of volume data - an image size, the number and thickness of slices
- The spatial deformation of discrete data grid, most frequently in MRI
- Noise in the image, mostly in MRI, depending on used sequence
- Motion artefacts - caused by patient movement during scanning
- Valuable artefacts - caused by the influence of certain substances whose properties significantly affect the outcome of scanning, such as metal implants etc., in CT

C. *Manipulation of 3D models*

The 3D model can be export from special medical segmentation software in 3D standard triangle language (STL) format. This file format is supported by many other software packages and it is widely used for rapid prototyping or computer-aided manufacturing (CAM). STL files describe only the surface geometry of a 3D object without any representation of colour, texture or other common CAD model attributes.

In Fig. 4 is shown the differences between original CAD model and STL model.

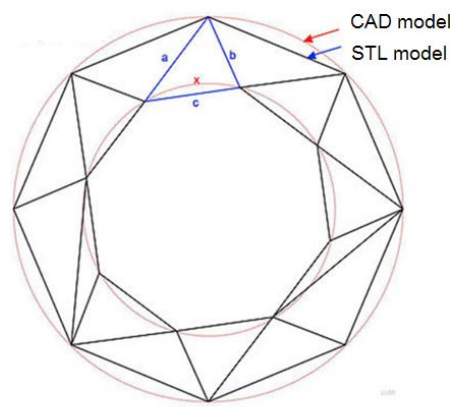

Fig. 4 Difference between original CAD model and STL model

Once the model in this format is exported to the CAD systems, the additional operation can be done. CAD systems support operation with model like merge, mirror, boolean, rescale and others, which can be helpful for designing of custom implants or for correction of the current model.

After designing a model in a CAD program, the design can be saved again as STL file, because most of the CAD programs have this function. The number and size of the triangles determine the accuracy of surface and the maximum distance between the surface original design and the new mesh of triangles has to be in tolerance. The same is valid for the angular deviation. Some components may not align correctly, so before saving the STL file, the geometry should be controlled. The designed model can contain some holes, gaps or overlaps which could affect the quality of printed models.

Prepared STL file in this manner can be used for 3D printing machines [30].

IV. Rapid Prototyping

RP is a group of techniques that are used for a rapid fabrication of physical parts from a 3D CAD models. All RP processes are based upon similar data pre-processing operations converting the virtual 3D models into 2D cross-sectional slices for each layer the machine will build. The fabrication is then based on additive layer manufacturing [31,32].

The first methods of additive layer manufacturing dates to the late 1980s and the produced objects served to be used as prototypes, that is why this technology is called RP.

Nowadays, produced parts can find a wide range of applications and one of them is also medical field, because the development of modern imagining modalities supported the compatibility to obtain continuous volumetric data sets, which provide the input data for 3D model generation. Common methods of RP which can be used today for medical application are: stereolithography, fused deposition modelling selective laser sintering and multi-jet modelling.

A. Stereolithography

It is the oldest method that utilizes the liquid photo sensitive polymer and ultraviolet laser to cure the layer as can be seen in Fig. 5.

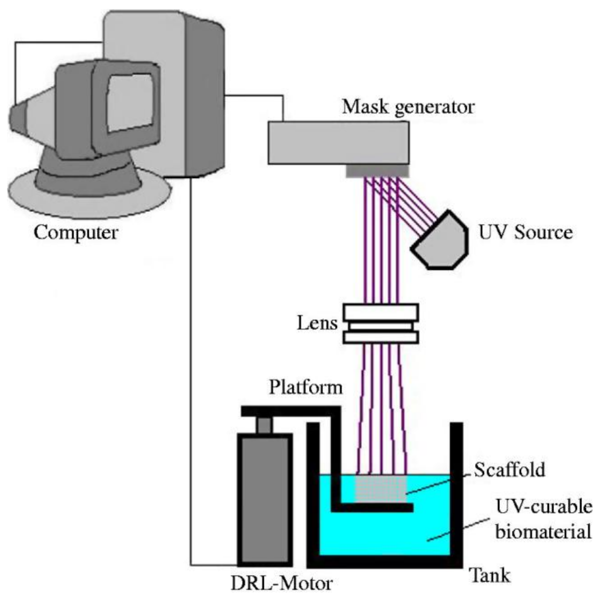

Fig. 5 The principle of stereolithography

The fabrication of model is done according the input data in the CAD model and then the process is fully automatic. The equipment for stereolithography consists of a moveable platform, which is immersed in the liquid resin at specific high. An ultraviolet laser with the beam focuses the optics and deflects mirror system stimulating the polymerization of the liquid. Then, the platform goes down a defined distance and the polymerized layer is covered with a new liquid layer. And in this way a model is build layer by layer. Stereolithography provides a good combination of accuracy and surface finish; the thickness of the layer is usually 0.1 – 0.5 mm. The main drawback is the limited section of materials.

B. Selective Laser Sintering (SLS)

This additive layer manufacturing utilizes a high power CO_2 laser to sinter (heat and fuse) material in form of fine powder. The laser selectively traces the cross-sectional profile of the part and after each cross-section is sintered, the powder bad is lowered by one layer thickness and a new layer of material is applied on top. This process is repeated until the final 3D shape is completed.

SLS can process many types of materials such as polymer, metal, and ceramics. In case of polymer, the technology is called selective laser melting. Fig. 6 illustrates schematically the SLS process.

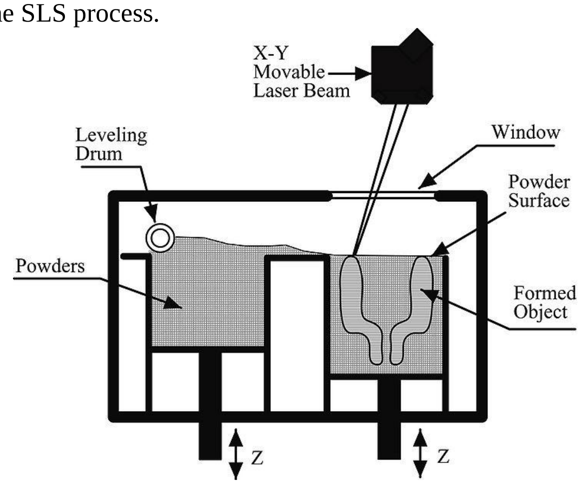

Fig. 6 The principle SLS

As can be seen, the laser melts selected areas of powder below it melting point and then lets it harden again. In this way the part is built up layer by layer. SLS does not require additive support material and instead of it uses an unsintered powder. The drawback of SLS is that the formed object has a rather porous surface which requires some post processing to smooth the surfaces.

C. Fused deposition modelling (FDM)

It is an RP process based on extrusion of the small amount of material through the orifice die which is heated just below the melting temperature of the material. Then, the semi-liquid material is deposited in very fine layers. As can be seen in Fig. 7, the building platform moves in x-y direction and the FDM head follows the tool path generated by the software. The raw material is in form of plastic filament or metal wire.

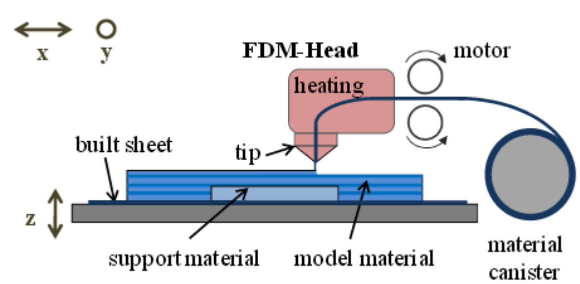

Fig. 7 The principle FDM

D. Multi-Jet Modelling

The 3D printers based on multi-jet modelling technology utilise a special print head with many small holes. The head jets the droplets of build material and support material simultaneously onto a build plate and creates one layer at a time. Each layer of material is then cured by ultraviolet lamp. The latest machines are capable to produce detailed models with layer thicknesses as fine as 16 microns [33]. The illustration of Multi-jet modelling process will be shown more detailed in section VI.

V. CASE STUDY

In this project, the vertebral column which provides protection for the spinal cord and branching nerves was chosen as the example on which can be shown how to process from 2D medical images until the real 3D anatomical objects.

A. Medical input data

The medical scan data of 33-year-old female was provided by Tomas Bata regional hospital in Zlín. This data was obtained from CT examination and shows a part of the body from the pelvis to neck. In the Fig. 8 is displayed one of the CT slice giving information of tissue in detailed cross-sectional view. As can be seen, X-ray radiation penetrated through the skin and soft tissue, while the bones appear white, because they absorb more radiation than other tissues that are grey.

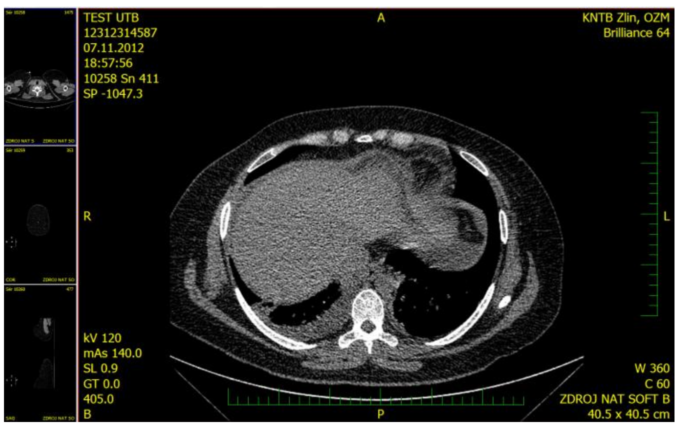

Fig. 8 The 2D CT scan after examination

The output 2D CT slices were saved in standardized format DICOM and could be only displayed as 3D preview in hospital software. The preview was not available to any changes and for further work the data was adjusted in the special medical software.

B. Processing of 2D data

For processing of medical scans, the special medical software Mimics developed by Materialise was used. Firstly, the 2D CT scans were uploaded in DICOM format and then the right orientation of images was performed. Ones, the working place was opened, all of the images were loaded and displayed in 3 planes, as is shown in Fig. 9.

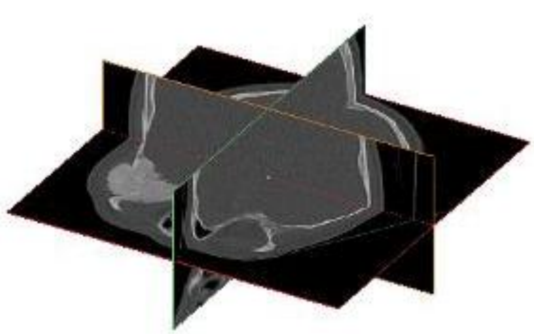

Fig. 9 Uploaded CT images viewed in 3 planes

After that, it was necessary to selected a region of interest and define a range of pixel grey values that interpret the object. In Fig. 10 is shown the Hounsfield scale that is a quantitative scale for describing radiodensity.

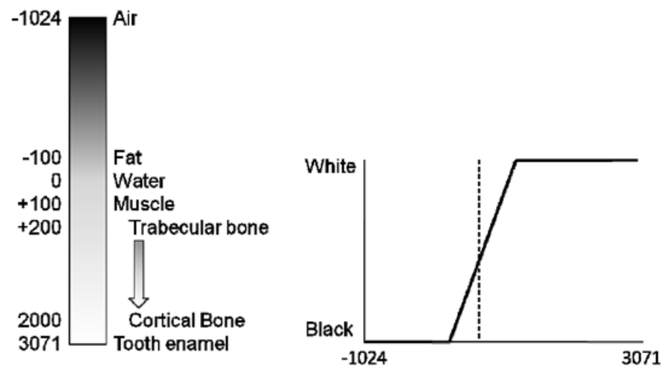

Fig. 10 Hounsfield scale describing radiodensity

In the Hounsfield scale the lower values demonstrate the soft tissues, while selection of higher values allows us to indicate only dense bones. Other step prior to creation of segmentation mask was thresholding. The regions with the same density according to Hounsfield scale were separated and the mask with coloured area was generated. In the Fig. 11 is shown the created segmentation mask and first preview which was calculated from the mask in each slide.

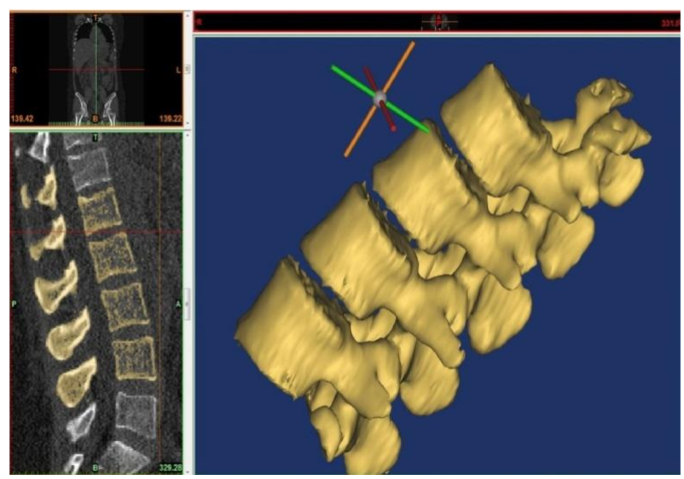

Fig. 11 The 3D preview with approximate shape of all vertebrae

As can be seen, the volumetric preview demonstrated approximately the shape of chosen vertebrae, but the anatomical structures contained many imperfections. The reason was due to segmentation based on automatically generated masks.

In other step, the manual editing of mask boundary had to be done in each cross-sectional slide. After that some smoothing operation was performed to obtain a high quality model. Finally, the volumetric preview could be recalculated from the coloured mask again.

Fig. 12 illustrates two vertebrae after their correction and as can be seen these anatomical structures are more accurate than the first volumetric preview. On these two vertebrae the mesh reconstruction was calculated and then the remeshed 3D models were exported into STL file.

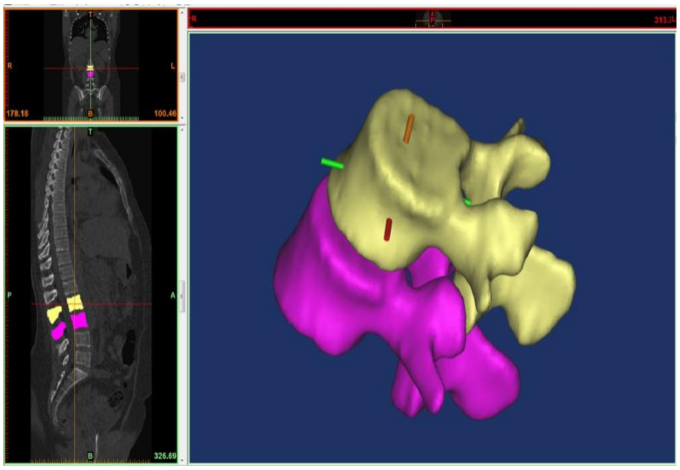

Fig. 12 The correction of chosen vertebrae tissues

C. Processing of 3D models

After all corrections and smoothing operations, the volumetric 3D models in STL format were imported separately to the CAD software Catia V5R18 developed by Dassault Systèms. Catia is traditional 3D CAD software equipped with 3D modelling tools for surfacing as well as functional tolerances. Fig. 13 shows the imported model of spinae vertebrae in CAD software Catia.

Fig. 13 Generated 3D models in CAD software

First of all, the models were moved into zero axis and then defects in the surface mesh composed of small triangular faces was corrected. In principle, for RP processes, a completely closed object is required, otherwise the small holes, gaps or overlaps can create errors in RP software. The process ended by exporting final models in STL format into 3D printer.

VI. Printing of models via Rapid prototyping

Printing of the real models was performed with a 3D printer Eden250 (Objet), which use the Poly-Jet method based on the jetting photo-sensitive polymer. The principle of this technology is displayed in Fig. 14. As can be seen, the photopolymer and support material were applied from the print head (with 96 jets) creating the ultra-thin layer of 0.016 mm onto the build tray. Immediately, after the jetting of a layer, the polymer was cured by UV light.

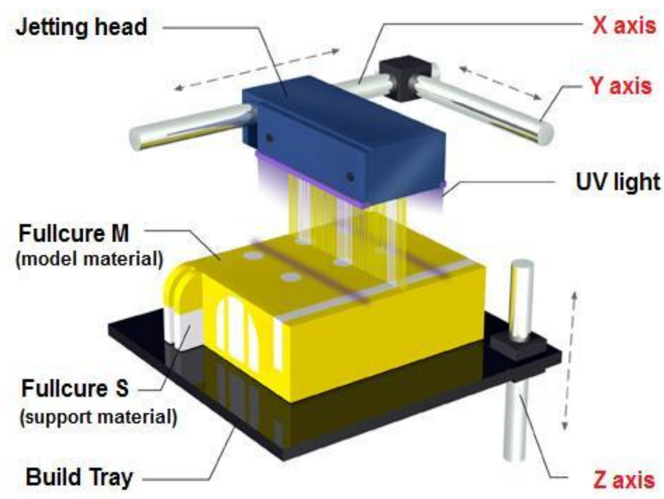

Fig. 14 Principle of polyJet method [34]

On the platform was possible to build both parts at same time. Fig.15 then demonstrates the printed part with support material which was based on gel. This gel could be easily removed from the prited part by hand.

Fig. 15 The 3D models of spinae vertebrae with the support material

Fig. 16 demonstrates the obtained 3D anatomical models with two different types of surface (A –smooth, B –matt), which was the option in RP software, after the removing of support material. The anatomical models had a surface with accuracy ranging from 0.05 to 0.1 mm.

Fig. 16 The final anatomical models with different surface quality. (a) Smooth surface, (b) Matt surface

For the printed models was used photo-sensitive polymer with the trade name VeroWhite, because the models have only demonstrative character; there were not any requirements on selected material. These anatomical models can serve only for preoperative surgical planning or medical training.

VII. Summary

The presented paper demonstrated in details how 2D medical image data can be converted into the real anatomical models. The medical scans are usually obtained in 3D volumetric sets from which is possible to create a 3D visualization of internal structure using some advanced medical software such as Mimics from Materialise. The visualization is based on volume rendering and medical segmentation where the quality of the virtual model will depend on scan resolution in pixels and the spacing between individual slices. For soft-tissue modelling are more appropriate the MRI scans, whereas for the hard-tissue is better to use CT images.

Once, the 3D visualization of desired tissue is obtained, most of the manual corrections have to be done, because the model will full of imperfections. For example, smoothing operation helps to adjust the surface quality of model, on the other hand too much smoothing will cause the divergences of the raw data and it is important to mention that also living tissue is not perfectly smooth. Especially, in case of elderly persons the bones will not have the same density and it would be difficult to identify the right shape. The same is valid for damaged tissue, where only specials can recognize the structures and it will be very problematic to build some real model from damaged structures. So, this kind of tissue may bring some limitations also with the designing of the customised implants.

For conversion of corrected 3D visualizations in to surface models, the triangular grid can be adopted and these models can also be converted to volumetric vector description with tetrahedral network, which allows continuous modelling of objects through numerical methods, for example finite Element Method (FEM). Another CAD software solution instead of Catia could be CAD doctor or 3-matic which contains many more advanced features like implant design. The final model can be than converted into STL format, which is supported mostly by all RP equipment.

Nowadays, there are many of RP methods and they number is still growing. The principles of most important were described in this paper, but all of them up to date are using the material which could not been used directly for medical implants and this bring the limitation only for pre-operative planning of for medical training models.

In the future, medical implant technology can continue to improve if classical materials for RP, will be replace with biomaterials. Generally, biomaterials are synthetic or natural origin materials that are intended for medical applications such as medical disposable supplies, prosthetic materials, dental and orthopaedic implants, polymeric drug delivery systems, products of tissue engineering etc. These materials must possess a lot of specific characteristics. The most important requirement is related with a biocompatibility. Thus, biomaterials must always be considered in their final fabricated and sterilized form.

The success of biomaterials in the body depends on many factors such as the material properties, design, and biocompatibility with the living tissue; other factors can include the surgery technique and health condition of patient. Biomaterials are quite different from other non-medical, commercial products in many aspects. For instance, the industrial manufacturing of biomaterials or the sale of medical devices, are allowed only if they clear strict governmental regulatory issues. The minimum requirements on the biomaterial for such governmental approval include non-toxicity, sterilizability, and effectiveness. In this context the main research issue is to develop and test materials that are biocompatible so that can be used safely for direct fabrication of implants.

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