# 3D modeling for augmented reality systems in novel vascular models


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## ABSTRACT

Endovascular surgery[1] is a continually developing branch of vascular surgery where the therapeutic intervention is performed from within the lumen of the vessel, usually under X-ray guidance. When the major artery of the body (aorta) becomes swollen (aneurysm), there is a danger of rupture, leading to catastrophic blood loss and death. An essential part of the procedure is pre-operative planning, taking accurate measurements of both the diameter and the length of the area to be excluded. There is no freely available, reliable, realistic simulator on which either the trainee can practice index cases or where trained surgeons can simulate more complex cases before they are performed on the patient. VR is developing and becoming more and more accessible. To be able to make the most of these tools we will explore the feasibility of using them for creating a 3D model of the aorta on which training can be carried out.



## CCS CONCEPTS

• **Software and its engineering** → Virtual worlds training simulations • *Computing methodologies → 3D imaging*

## KEYWORDS

Virtual Reality, Augmented Reality, 3D modelling

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## 1 INTRODUCTION

Endovascular aneurysm repair (EVAR) is a procedure that repairs an aneurysm in the aorta. An aneurysm is an abnormal swelling/ballooning of part of the aorta. It weakens the wall of the aorta, which will eventually lead to rupturing of the aorta causing catastrophic consequences. Men over the age of 60 are at higher risk of an aneurysm. The procedure that is used is a minimally invasive surgery, where two incisions are made in the groin to expose the femoral artery in order to insert the graft and stents, which are shown in Figure 1. This is done with the aid of guidewires to ensure that the graft is positioned correctly above and below the part that is swollen in the aorta. Before EVAR surgery was used, open surgical repair was the main interventional procedure, which has a high chance of mortality within 30 days following the surgery, in between 4%-12% of patients. Compared to EVAR, in which the grafts are durable for 20-30 years succeeding the procedure and function effectively in most patient for the rest of their lives, making this a favorable repair technique. If an aneurysm isn't treated the consequences are lethal with a 90% mortality rate [1]. EVAR may not be suitable for all patients and a CT scan is used to determine the diameter suitability, in which the length and quality of the aorta below the renal arteries (aortic neck) and femoral artery access vessels are determined.

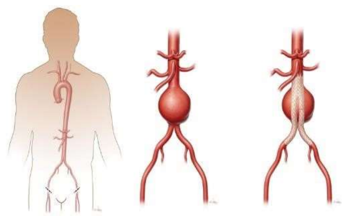

**Figure 1: Aneurism Repair**

3D Modelling of the anatomy uses data from scanners such as MRIs, CT scans and ultrasounds. These data sets usually come as DICOM (Digital Imaging and Communications in Medicine) files which are then imported into graphical software, which transform these data sets into 3D geometric interpretations, using various different algorithms. Segmentation is performed on the “slices” (images in the data set) of the anatomy, followed by the reconstruction of the model. Firstly, a label map is created to identify the individual structures, followed by the use of interpolation algorithms such as, marching cubes, to create a surface model and finally a mesh is generated. The limitations of these structures such as the triangulated and quadratic geometric surfaces include:

- Accurate representation of the anatomical geometry, but is not easily deformed
- Easily deformed and manipulated but do not offer an accurate representation of the anatomical structure.

For this project, marching cubes will be used for creating the surface from the DICOM data-set. Most modelling software use this algorithm, although other algorithms may be used which, will be discussed further in the report. After constructing the surface, an STL (stereolithographic) file, which will be imported into UNITY game engine, is created. This will be imported into a 3D interactive environment using ARTOOLKIT, an augmented reality library, to add positional tracking and later placed in the Oculus Rift. VR is not a completely new area for medicine and there are already many medical applications, especially in training and education. We will explore in this project the feasibility of using consumer VR products that have been developed to perform the same objective as industry tools. The feasibility will mean a decrease in costs in creating cheaper options for the already present tools used in education and in surgery training.

# 2 BACKGROUND RESEARCH

## 2.1 3D Modelling and Printing in Medicine

EVAR surgery is aided greatly with the use of 3D reconstructions and Doyle et al [2] discusses the benefits it incurred on the planning of the surgery and measurement required of the anatomy, that may have been difficult to obtain from the 2D scans. The scans of the aorta were taken using slices of 3mm apart. Mimics v12 (Materialize, Belgium) was the tool used for the reconstruction of the model while the study also included the use of finite element analysis to provide a measure for the stress experienced by the aortic to assess the risk of rupture due to the swelling. A thresholding technique is used on the scans for the segmentation of the image and this is acquired by providing an assessment of the pixel and assigning intensity levels measured in HU (Hounsfield units). The wall stress levels were determined using the FEA method which subdivided the structure, after which each divisions’ stress is computed using the software ABAQUS v6.7. The study assumed a uniform wall thickness of 1.9mm and modelled as a “non-linear hyperelastic material”. The 3D model reconstruction was said to take only 2 min for a basic model and 1hr for a detailed model. EVAR stent grafts require accurate neck diameters, iliac diameter and also the length of the device is important. The 3D model allowed for decisions, regarding newly highlighted issues with the model to be made prior to the surgery. In conclusion the 3D models are proven to be of great help in determining the degree of curvatures and length which helps in procedure preparation for patient specific cases.

Doyle, et al. [3] explained how the CT scans from the previous article were reconstructed and printed. Mimics Materialise is the software used to segment and convert the CT scans into a 3D geometric representation. The marching squares algorithm was used to determine the contours of the image and segment the parts of the scan that are needed according to a predetermined grayscale value. The details of the model depend on what they are required for, for example iliac arteries are believed to be important for testing stress levels while unimportant for stent graft testing. PROENGINEER was used to design the models from this 3D reconstruction which is then exported into AlphaCAM to configure for the milling machine. Wall thickness was measured 40 to 60 times for each model which was then averaged. The study also aimed to discuss the benefits of using the model in performing numerical analysis on the wall stress to predict the possibility of a rupture in AAA (abdominal aortic aneurysm repair).

Maleike et al [4] propose a free tool for medical image segmentations and discusses freely available software that do the same**.** MIPAV1, MeVisLab2, 3D Slicer, Seg3D, Caret, and ITK-SNAP are mentioned in the article. Some of these software’s focus on manual segmentation. ITK-SNAP uses semi-automatic segmentation and uses active contour methods, as well as manual delineation. Interpolation of unsegmented images slices from neighbouring segments, full multi-level redo and undo are the functionalities that this tool is proposing solutions for. The tool developed in this article is InteractiveSegmentation, which is based on MITK (Medical Imaging Interaction Toolkit). The article discusses how the tool is different from other software and explains how it deals with typical issues that arise during the segmentation process E.g. Leakage during the segmentation, this is where, parts of the segmentation leak into neighbouring structures. The toolkit also offers interpolation, which is used to speed up the segmentation process especially with the high number of slices being worked on. It offers this as a suggestion which can be undone if needed, a functionality that is not implemented in other tools. The toolkit also suggests methods that help the automatic segmentation when parts of the object aren’t being segmented correctly, such as learning algorithms from available datasets that may aid future segmentations.

Pavarino, et al [5] have tested the integration of free mesh generating software’s tools with Open Source software such as Blender, solid modeler and TetGen for mesh generation, and automatic mesh generator that uses the Delaunay tetrahedralization. This is not considered to be the most accurate algorithm and other algorithms are needed to improve on the final mesh. Blender is available under dual license Blender License and GNU license, and "contains resources to export and import objects in different formats, through scripts. Scripts are useful for automating methods, navigating and manipulating the discretized geometric domain." Automatic generation of tetrahedral meshes is not a trivial task and in this article the motivation behind the use of the Delaunay algorithm is that it's the most widely used and most efficient algorithm. Furthermore, this is available for use in the TetGen software, which is a free mesh generation software. Representation of sharp angles of 30 and 60 degrees, is a difficulty experienced in the construction of the atrium, while some structures were considered much simpler to define as they were regular cylindrical shapes. The strategy recommended in this article for the smooth representation of sharp angles is to increase the number of vertices. This article concludes with promising results for the reconstruction of 3D heart simulation with a quality that can be used in simulation by the finite element method. The article doesn't discuss the use of this technique with patient specific data, but offered an alternative to the use of paid software.

Ayyalasomayajula [6] describes in detail a method to reconstruct AAA (Abdominal Aortic Aneurysm) geometry from CT images while trying to utilize inexpensive resources and minimal user intervention. MATLAB was used to reconstruct the geometry, with the implementation of the active contour technique to segment the region of interest. The main difficulty in the reconstruction of AAA models, is distinguishing the aortic wall from the rest of the image due to poor contrast from the CT scans. After exporting the model into MATLAB, SVM (Support vector machine) was used to smooth the model. The scans were obtained using 32 or 64-slice machine with 1mm thick detector collimation. The intensity of the CT images determines the accurate segmentation of the images, while the irregularities of the structures also affect the segmentation. Therefore, the algorithm chosen has to be capable of determining the concavity and convexity of the anatomical structure. The study used active contours for the segmentation to be able to take this into account. Firstly, an initial surface is computed then applied. A snake, which diffuses in the image using the gradient vector field to be able to determine the edges and contours of the image is used. The algorithm was applied multiple times to achieve optimal snake parameters. The contrasting agent used to scan the images was beneficial for the segmentation of the lumen but was not good for the wall segmentation as the GVF isn't capable of accurately detecting the boundaries. The study describes another method used to segment the wall which entailed the use of another snake for the segmentation with a stiff surface. The study claims that use of the SVM for the smoothing of the model guarantees curvature continuity which is important for the development of the automated and smooth meshes.

## 2.2 Algorithm

Marching cubes [7]: the most used algorithm in medical image 3D surface construction, being an easy and widely used algorithm. The algorithm creates "triangle models of constant density surfaces from 3D-medical data" by dividing the region of interest into cubes and then creating triangles for which the normals to the surface at each vertex of each triangle are calculated. It iterates over a grid of cubes that are superimposed over a region on a function and if all 8 vertices of the cube are below or above then they are not discarded and are considered part of the surface otherwise some vertices and triangles are generated. With 8 vertices there are 256 ways a surface can intersect the cube. A lookup table is generated for surface-edge intersections. Triangulation for each case has proven to be either a rotation or mirror of 15 unique patterns, see **Error! Reference source not found.**, and therefore reduces the number of triangulation computation required. An index is given to each case which will tell which edge the surface intersects then a linear interpolation is used along the edge of the surface intersection. It uses information from the original data to determine inter-slice (real-world depth) connectivity between each slice, surface location, and surface gradient. The resulting triangle model can be displayed using standard rendering algorithms.

Level set segmentation is a technique [8] used when slicing the images because with an aneurysm, the cross section is not circular and can exhibit concave divergence. Geodesic Active Contours were used to obtain the curve that was then inserted into the image and allowed to deform based on a curvature dependent speed which stopped once it reached the boundaries of the object.

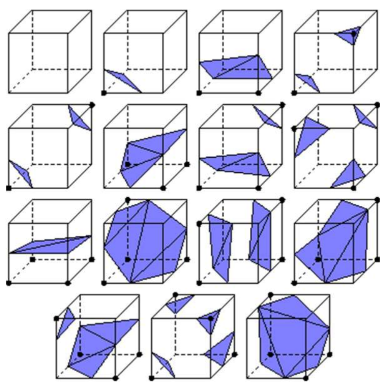

**Figure 2: Marching Cubes - The originally published 15 cube configurations**

# 3 IMPLEMENTATION

## 3.1 Segmentation and Mask selection

Segmentation is used to divide the CT images so it would include only the structure of interest, for easier manipulation. There are many different algorithms that can be used for the segmentation of the region of interest. There are automatic, semi-automatic and manual segmentation methods, where the use of each depends on the task that is required to be accomplished. Automatic segmentation of medical images is considered to be a difficult task with complex structures, that often do not exhibit any simple linear features as well as artefacts resulting from the quality of the DICOM data sets obtained from the scans, which include:

- Intensity inhomogeneity
- Grey levels of different tissues difficult to distinguish
- Artefacts

Manual segmentation involves manually marking the boundary of the region of interest, which may not be suitable for larger structures. For this project a semi-automatic segmentation technique based on Hounsfield scale, a grayscale that describes radio density allowing for the distinction of air, water, muscle, fat and bone, was used. To find the most suitable software to accomplish this, many different open-source and free tools were tested, including 3DSlicer, ImageJ and InVesalius. For the purpose of this project InVesalius was the most suitable software to use, as it provides semi-automatic, manual segmentation. The software also provides pre-defined masks for most human tissues including bone, fat, muscle and other tissues, by utilising the Hounsfield scale to determine the tissues of interest.

## 3.2 Surface

After loading the DICOM data set into InVesalius a mask must be constructed, either by choosing from the pre-defined tissue masks or by creating a boundary to include the region of interest. InVesalius allows for manual modification of the masks where multiple masks can be created and then Boolean operation can be applied to them such as union, intersection and difference. To obtain the mask, the bone pre-defined threshold was used. As demonstrated in Figure 2, the bone mask also highlights the spine and the scanning table, which will have to be removed using a mesh manipulation tool as it was difficult to remove. Removing the unwanted parts using InVesalius would require manually selecting those regions slice by slice and therefore another software was determined to fulfil this task. Most software's use marching cubes to construct the 3D surface of the model as its reasonably simple to understand and is efficient in rendering constant density iso-surfaces, which is what InVesalius employs to construct the surface. Considering that InVesalius is mainly used for rapid-prototyping and imports files as OBJ, STL and PLY formats it was the appropriate choice for constructing the initial model.

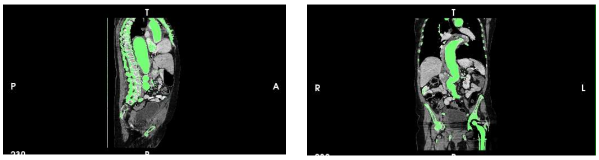

**Figure 2: Pre-defines Bone Mask**

## 3.3 Modelling

After obtaining the surface, the removal of the bones and the unwanted parts was done using a mesh manipulation open-source software, MeshLab. MeshLab helps in processing large unstructured models providing tools for editing, cleaning, healing and rendering. Selecting the unwanted components using MeshLab's selection helped in speeding up the process, but some parts required careful selection where select faces in a rectangular region was used. After removing the unwanted parts, the model had many holes that needed to be filled which was carried out with MeshLab's fill holes filter, which required the removal of all manifoldness from the model. After doing so it was important to not fill the iliac artery for use further in the development for the surgery simulation. Re-meshing of the model was also required to remove the resulting noise from generating the surface, which included the stairway affect, holes or the diamond artefact (where triangles making up the surface become visible). These are known artefacts associated with using marching cubes. The stairway artefact mainly affected this project, which occurred in areas where there was a large difference between the segmented and non-segmented data, with clusters that consist of high values and others of zero values resulting in the normals getting distorted and the surface not being rendered smoothly.

After the removal of the bones and unwanted regions of the model, the vertices and faces removed produced many new holes in the model, which were again filled and the model was smoothed using Laplacian smooth. This algorithm preserves the topology of the mesh and simply uses the average of the neighbouring vertices to move the vertices around, while also preserving the number of vertices and triangles. Later on in the development it was determined that the vertex and polygonal count must be reduced, in which the quadratic edge collapse decimation was used using the following parameters to preserve the topology of the mesh:

The final model was then exported as STL to be manipulated in MeshMixer, where it was sliced to enable part selection to fulfil the discretionary part of this project.

## 3.2 Slicing

The model was initially imported into UNITY3D game engine where the mesh was separated into multiple parts that didn't correspond to any specific part of the aorta, which is required to implement the highlighting regions of interest functionality. After researching many different open-source tools that enable slicing such as Blender, NetFabb and MeshMixer, it was determined that MeshMixer was the most ideal. The other tools either added faces that covered the sliced region, or were time consuming as the model was too large and was computationally expensive to manipulate. In Blender the plane cut method was used to try to slice the model into the different parts, this effected the rendering process as blender deletes one of the sliced parts which required the duplication of the original model and this crashed the software. MeshMixer is a free software tool by Autodesk, that cleans 3D scans and prepares meshes for 3D printing.

The sliced parts were exported as OBJ files and imported into UNITY3D to ensure that meshes were not split into multiple parts.

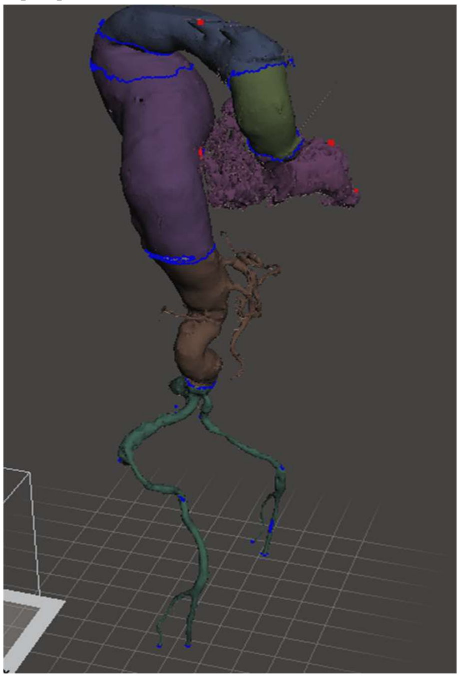

**Figure 3: Meshed Mixer - Sliced model**

The reconstruction of the 3D model required multiple software testing prior to the final mesh generation. Some of the tools required a steep learning curve, resulting in the testing of multiple others pending a much versatile tool. The most time-consuming steps during the construction, were the mesh cleaning and the slicing of the model. For the cleaning step of the model, the laptop used for the modelling could not handle the extensive vertex and face selection operation, which resulted in the crashing of the software on multiple occasions and no cleaning could be completed. This is mainly due to the segmentation technique used which didn't isolate the region of interest without other parts of the anatomy also being selected. The model is of high vertex count and is of high quality. To determine this, an expert in medical anatomical structures was consulted and the model was evaluated as being highly accurate.

## 4 DISCUSSION

The tools used in this project are comparable to those used in the industry, and can be integrated to create a tool that could be used for medical education and surgery training. The final models have been or can be then used in an augmented reality or VR environment. Semi-automatic segmentation of the model indicates that the process of constructing a 3D model from DICOM can be done but may be inaccurate due to the scanning resolution used. In regards to the accuracy of the models, they are dependent on the quality of the scans and the segmentation techniques used to extract the 3D data. The project contained multiple elaborate components, such a medical imaging, 3D model construction, mesh manipulation, virtual reality, augmented reality and game development. These different areas needed much research and had a steep learning curve but it was determined that it is feasible to create a medical VR and AR tool using the tools mentioned above, provided that the models are constructed manually. With the many different VR and hand tracking technologies currently being developed, the possibilities for the creation of highly accurate and sensitive training and educational tool can be developed. Such as the Leap Motion hand sensors, Vive, Oculus Rift and many more.

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