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Master's Thesis

Fully Automatic Blood Vessel Branch Labeling

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Abstract

Volume representations of blood vessels acquired by 3D rotational angiography are very suitable for diagnosing a stenosis or an aneurysm. For optimal treatment, the shape parameters of the diseased vessel parts are needed by physicians. Therefore, a fully-automatic extraction of this shape from such a volume representation has been developed. The demo program v3d_main has been developed to test the various algorithms, such as the segmentation algorithm, the wave propagation algorithm and the thinning algorithm.

This paper first discusses and analyses the blood branch labeling acceleration algorithms, and proposes two methods for improvement. The first one is called the surface wave propagation method which restricts the wave moving only along the blood vessel surface. This method is applied to detect the extremities of the vessel voxel structures. The second one combines a thinning algorithm with the surface propagation to extract the center lines and the bifurcations of the blood vessels, which also gives the vessel voxels a unique number (label) per vessel branch.

Proper validation results are given in this report. The result shows that the two methods can substantially decrease the computation time and keep the labeling accuracy. However, whether the branch labeling result, generated by surface wave propagation based on a vessel graph, are suitable for computer assisted diagnosis has not been investigated yet.
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Chapter 1

Introduction

A cerebral aneurysm (also called intracranial aneurysm) in the brain is a weak spot on a blood vessel that bulges outward and fills with blood. Brain aneurysms are common in adults, according to angiography and autopsy studies[1]. It can put pressure on a nerve or surrounding brain tissue. It may rupture, lead to a stroke, brain damage and even death. Brain aneurysms can occur anywhere but most of them are located on the arteries in the brain.

Atherosclerosis, for example coronary artery disease (CAD), is another vascular disease. Plaque builds up inside the coronary arteries. These arteries supply heart muscle with oxygen rich blood. Plaque is made up of fat, cholesterol, calcium and other substances. When the plaque cracks, it causes blood cells called platelets (PLATE-lets) to clump together and form blood clots at the site of the cracks. The arteries narrows decrease or prevent blood flow causes a heart attack.

Both of these two diseases can be treated by surgery guided by medical imaging technology such as 3D Rotational Angiography (3DRA).

1.1 Medical imaging technology

Integris Allura X-ray system is a fully digital 3D Rotational Angiography system, developed by Philips Medical Systems. It enables physicians to capture and view detailed 3D images of a patient vascular structure, leading to faster and more accurate diagnosis and treatment of vascular disease. The 3DRA system provides enhanced diagnostic capabilities for aneurysm and carotid artery disease. It is increasingly used to diagnose brain aneurysms and to decide on the optimal treatment modality. It provides high-resolution, quality 3D image data that is acquired during the normal diagnostic workup [2, 3]. Using the 3DRA technique, physicians can assess the aneurismal neck, including its shape, size, and relationships with neighboring vessels [3]. During surgery of brain aneurysms, additional small angiographic occult aneurysms are commonly found. With 3DRA even small aneurysms can be more easily depicted than with digital subtraction angiography (DSA) [4].
1.2 Aneurysms and stenosis labeling

3DRA is suitable for diagnosis of the brain aneurysm and CAD. It applies 3D reconstruction techniques to the image data acquired in rotational angiography. The volume rendered images have high resolution and can be rotated to show the vascular structures from any angle [5]. The volume representations of blood vessels have a clear distinction in gray values between tissue and vessel voxels. Therefore, they are suitable for aneurysms and stenosis diagnosis [6]. For optimal treatment of an aneurysm, physicians need to know the volume and shape of the aneurysm and then treat it by endovascular coiling. A method for fully-automatic labeling of normal blood vessels voxels was developed [6-8]. It starts with the detection of the extremities of the vessel in the segmented volume. It can label the vessel vertices with a unique number per vessel branch. Hence surface vertices of neighbor vessel branches can be separated according to their different label.

The similar technique can be used to detect and label the stenosis in 3D images of 3DRA. It can indicate the location and calculated the stenosis degree to assist the physicians treat the patients.

1.3 Research question

The branch labeling method consists of five main parts, and the first two of them are time consuming. In the first part, a wave propagation method is applied to detect the extremities of the voxel vessel structures [8]. Then a peeling processing extracts the blood vessel center lines according to the detected extremities, and labels the vessel voxels with different branch numbers. Now in the first part, location of the extremities at the boundaries of the volume is easy and fast. But to find the extremities of the vessels inside the volume is done by means of a time consuming wave propagation algorithm. A faster detection of the inner extremities in the segmented volume is required. A possible approach is to down sample a segmented volume to a smaller volume by combining 2x2x2 voxels to one new voxel.

Another approach for faster detection of extremities is investigated. Currently, the main algorithm for detection of the extremities consists of wave propagation through the vessel voxels of the segmented volume. The computing time depends mainly on the generation of a new wave from an old wave. If the inner vessel voxels can be ignored by giving them a special label, the
waves will be much smaller because only the surface vessel voxels (i.e. the vessel voxels with a tissue voxel as face neighbor) will be included. In this case the waves will propagate only along the vessel surface. The first question is whether to assign this special label takes less time than the time saved during wave propagation and can be done during the already present component labeling procedure. The second question is whether the set of extremities detected with this new algorithm corresponds to the set of extremities found with the original wave propagation algorithm, which means the number of extremities should be the same and the extremity voxels should be located in the same extremity.

An approach for faster branch labeling is also investigated in this project. The wave propagation method of Zahlten labels the original gray value volume using an appropriate threshold and generates the corresponding vessel graph. However this method is not accurate enough at the junctions (bifurcations), see Figure 4.8. A thinning method is used after a wave propagation in [7]. A segmented voxel volume with the extremities is set as the input data; it is peeled in a number of iterations. The resulting skeleton of branches and bifurcations is a better approximation of the vessel graph than the method of Zahlten. However the thinning is a time consuming approach for the bifurcation position correction. In this thesis, the surface wave propagation is used to not only detect the extremity but also to extract the centerlines and bifurcations.

1.4 Overview of contents

After this introduction, in Chapter 2 some medical information is given, to provide insight into the pathology of the aneurysm and the mechanism of CAD. In Chapter 3, we pay attention to the research software environment the Demo program in which these algorithms have been developed. Afterwards, Chapter 4 gives some detailed information about the fully automatic branch labeling of voxel vessel structure, in order to explain the acceleration or improved methods clearly. Subsequently, the acceleration methods of the faster detection of the extremity are discussed; beginning with the down sampling then the surface wave propagation is introduced in Chapter 5. The centerlines extraction and bifurcations detection by the surface wave propagation are presented in Chapter 6, while the validation of these two methods are
given in Chapter 7. Eventually, the conclusion of this thesis is discussed in Chapter 8 and some suggestions for future work.

The research software environment *the Demo program* is developed by my supervisor Jan Bruijns. And he also gave me some idea about the down sampling method and the surface wave propagation. All the display functions in the project are implemented by him.
Chapter 2

Medical background

The medical information in this chapter mainly is cited from the following websites:

2.1 Pathophysiological background

2.1.1 Aneurysm

There are three types of aneurysms: the aortic aneurysms, cerebral aneurysms, and peripheral aneurysms. The aorta is the main artery in the human body, which carries blood with rich oxygen from the heart to other arteries, as shown in Figure 2.1 A. Most aneurysms occur in the aorta. The aortic aneurysm can be a thoracic aortic aneurysm (TAA) or abdominal aortic aneurysm (AAA). TAA occurs in the part of the aorta flowing through the chest. They can be detected by chest Computed Tomography (CT) scans. Similar to the TAA, an AAA occurs in the part of the aorta running through the abdomen, which can grow very large without producing symptoms.

Brain aneurysms are often discovered when they rupture, causing bleeding into the brain or the space closely surrounding the brain called the subarachnoid space, causing a subarachnoid hemorrhage. Subarachnoid hemorrhage from a ruptured brain aneurysm can lead to a hemorrhagic stroke, brain damage and death. A typical brain aneurysm can be seen in Figure 2.2, the inset image shows a close up of the aneurysm.

Sometimes patients describing "the worst headache in my life" are actually experiencing one of the symptoms of brain aneurysms related to having a rupture.

2.1.2 Coronary artery disease

Coronary artery disease (CAD) is the most common type of heart disease. According to the report from national Heart Lung and Blood Institute in the United States, CAD is the leading cause of death for both men and women in the United States. There are more than half a million Americans die from CAD each year.
Figure 2.1 Symbol A: a normal aorta. Symbol B: a thoracic aortic aneurysm. Symbol C: an abdominal aortic aneurysm. (From www.nhlbi.nih.gov)

Figure 2.2: A cerebral aneurysm in the brain. (From www.nhlbi.nih.gov)
CAD happens when the coronary arteries become hardened and narrowed. The plaque, buildup of cholesterol and other material in blood, grows on the inner walls of blood vessels. From Figure 2.3, a plaque grows and narrows the artery, reduces and even prevents the blood flow to the heart muscle. As a result, the heart muscle cannot receive enough blood with oxygen. This can cause angina pectoris or a heart attack. Angina pectoris is chest pain or discomfort that occurs when the blood flow is not enough to an area of the heart muscle.

![Diagram showing normal artery and artery with plaque buildup.](From www.nhlbi.nih.gov)

A heart attack happens when a blood clot blocks blood flow at the narrowed artery completely, causing permanent heart damage because the area of heart muscle dies. An overview of a heart and coronary arteries are shown in Figure 2.4. The dead heart muscle (dark area) was the result of a heart attack. Most heart attacks involve discomfort or chest pain in the center of the chest, which can last for few minutes. They also can cause upper body discomfort in one or both arms.
Figure 2.4 Symbol A: an overview of a heart and coronary. Symbol B: a cross-section of the coronary artery with plaque. (From www.nhlbi.nih.gov)

2.2 Diagnosis

2.2.1 Aneurysms

Most aneurysms develop slowly for years without causing any signs or symptoms until they rupture or are detected by brain imaging. There are several diagnostic tests or procedures available to provide information about the aneurysm.

Angiography is a dye test used to analyze the arteries or veins. An intracerebral angiogram can detect the degree of narrowing or obstruction of an artery or blood vessel in the brain, head, or neck, and can identify changes in an artery or vein such as a weak spot like an aneurysm. It is used to diagnose stroke and to precisely determine the location, size, and shape of a brain tumor, aneurysm, or blood vessel that has bled. This test is usually performed in a hospital angiography suite. Following the injection of a local anesthetic, a flexible catheter is inserted into an artery and threaded through the body to the affected artery. A small amount of contrast dye (one that is highlighted on x-rays) is released into the bloodstream and allowed to travel into the head and neck. A series of x-rays is taken and changes, if present, are noted.
Computed tomography (CT) of the head is a fast, painless, noninvasive diagnostic tool that can reveal the presence of a cerebral aneurysm and determine, for those aneurysms that have burst, if blood has leaked into the brain. This is often the first diagnostic procedure ordered by a physician following suspected rupture. X-rays of the head are processed by a computer as two-dimensional cross-sectional images, or “slices,” of the brain and skull. Occasionally a contrast dye is injected into the bloodstream prior to scanning. This process, called CT angiography, produces sharper, detailed images of blood flow in the brain arteries. Diagnosis of a ruptured cerebral aneurysm is commonly made by finding signs of subarachnoid hemorrhage on a CT scan as shown in Figure 2.5.

Figure 2.5 C-arm CT scan (From www.brainaneurysm.com)

Magnetic resonance imaging (MRI) uses a combination of a powerful magnetic field, radiofrequencies, and a computer to produce detailed images of the brain and other body structures. Magnetic resonance angiography (MRA) produces more detailed images of blood vessels. The images may be seen as either three-dimensional pictures or two-dimensional cross-slices of the brain and vessels. These painless, noninvasive procedures can show the size and shape of a ruptured or an un-ruptured aneurysm and can detect bleeding in the brain.

Cerebrospinal fluid analysis may be ordered if a ruptured aneurysm is suspected. Following application of a local anesthetic, a small amount of this fluid (which protects the brain and spinal
cord) is removed from the subarachnoid space—located between the spinal cord and the membranes that surround it—by surgical needle and tested to detect any bleeding or brain hemorrhage. In patients with suspected subarachnoid hemorrhage, this procedure is usually done in a hospital.

### 2.2.2 Coronary artery disease

No single test can diagnose CAD. When doctor thinks the patient have CAD, one or more the following tests probably will be taken. An Electrocardiogram (ECG) is a simple test that detects and records the electrical activity of the heart. An ECG shows how fast the heart is beating and whether it has a regular rhythm. It also shows the strength and timing of electrical signals as they pass through each part of the heart. Certain electrical patterns that the ECG detects can suggest whether CAD is likely.

An echocardiography test uses sound waves to create a moving picture of the heart. It provides information about the size and shape of the heart and how well the heart chambers and valves are working. This test also can identify areas of poor blood flow to the heart, areas of heart muscle that are not contracting normally, and previous injury to the heart muscle caused by poor blood flow.

A chest X-ray takes a picture of the organs and structures inside the chest, including the heart, lungs, and blood vessels. It can reveal signs of heart failure, as well as lung disorders and other causes of symptoms that are not due to CAD.

Coronary angiography and cardiac catheterization uses dye and X-ray to show the insides of the coronary arteries. To get the dye into the coronary arteries, the doctor will use a procedure called cardiac catheterization. A long, thin, flexible tube called a catheter is put into a blood vessel in the arm, groin (upper thigh), or neck. The tube is then threaded into the coronary arteries, and the dye is released into the bloodstream. X-rays are taken while the dye is flowing through the coronary arteries. Cardiac catheterization is usually done in a hospital. The patient is not awake during the procedure. It usually causes little to no pain, although the patient may feel some soreness in the blood vessel where the doctor puts the catheter.
2.3 Treatment

2.3.1 Brain aneurysms

To get to the aneurysm, surgeons must first remove a section of the skull, a procedure called a craniotomy. The surgeon then spreads the brain tissue apart and places a tiny metal clip across the aneurysm neck to stop blood flow into the aneurysm. After clipping the aneurysm, the bone is secured in its original place, and the wound is closed.

Surgery or minimally-invasive endovascular coiling techniques can be used in the treatment of brain aneurysms. It is important to note, however, that not all aneurysms can be treated at the time of diagnosis or are amenable to both forms of treatment. Patients need to consult a neurovascular specialist to determine if they are candidates for either treatment.

Figure 2.6 Endovascular Coiling v. Surgical Clipping (From www.brainaneurysm.com)
2.3.2 Coronary artery disease

Treatment for CAD may include lifestyle changes, medicines, and medical procedures. Regular physical activity and maintaining a healthy weight can lower many CAD risk factors. If lifestyle changes are not enough, taking medicines is good treatment for CAD. If patient situation is even worse, a medical procedure is necessary. Angioplasty (explained in the sequel) is used as treatment.

Angioplasty opens blocked or narrowed coronary arteries. During angioplasty, a thin tube with a balloon or other device on the end is threaded through a blood vessel to the narrowed or blocked coronary artery. Once in place, the balloon is inflated to push the plaque outward against the wall of the artery. This widens the artery and restores the flow of blood. Angioplasty can improve blood flow to the heart, relieve chest pain, and possibly prevent a heart attack. Sometimes a small mesh tube called a stent is placed in the artery to keep it open after the procedure.

Picture A in Figure 2.7 shows the deflated balloon catheter and closed stent inserted into the narrowed coronary artery. The insert image on picture A of Figure 2.7 shows a cross-section of the artery with the inserted balloon catheter and closed stent. In picture B in Figure 2.7, the balloon is inflated, expanding the stent and compressing the plaque to restore the size of the artery. Picture C of Figure 2.7 shows normal blood flow restored in the stent-widened artery. The insert image shows a cross-section of the compressed plaque and stent-widened artery.
Figure 2.7: The placement of a stent in a coronary artery with plaque buildup.

(From www.nhlbi.nih.gov)
Chapter 3

Software environment

The introduction of the research tools in this chapter is extracted from the confidential reference manual.

C++ is the dominant language for CAD software development, and the same C++ code can be practically compiled in almost any type of computer and operating system without making any changes. Linux is a complete operating system with many technical merits such as it is a stable, reliable and extremely powerful. It comes with a complete development environment, including C, C++. It is easier to do programming work in Linux or UNIX than Microsoft windows. The requirement from Philips Medical Systems is using C++ as algorithm development language. The demo program is being developed under Linux but the resulting code, except for the user interface part, is combined with the software of Philips Healthcare built under Microsoft windows.

3.1 Demo program

The demo program, v3d_main (see Figure 3.1) had been developed to test the various algorithms, such as the segmentation algorithm, the wave propagation algorithm and the thinning algorithm. Most of the algorithms in the demo program can be called directly by other application programs.

3.2 V3D functionality

The demo program has nine windows. The eight windows labeled “Control”, “Segment functions”, “Surface functions”, “Trace functions”, “CATP functions”, “Cardio functions”, “Special functions” and “Navigate functions”, contain the graphical user interface. The window labeled “Display” contains the pictures generated by the demo program. The windows “Special functions” and “Navigate functions” are intended for testing only.

All control functions are protected against premature use. For example clicking the “segmentation thresholds” action button has no effect when the volume dataset is not available.
yet. The actions to generate the missing entities are started automatically. For instance clicking the “segmentation thresholds” action button without a 16 bits gray value volume data forces a program generated clicking on the “new volume” action button after which the original action is executed. If the missing entities are still missing, a message is shown and the action ignored. State variables are used to implement this protection.

Figure 3.1 The main interface of the demo program v3d_main

3.3 The main control functions

Not all the control functions will be introduced, only some of them, which are often used, are described in this section. The “new volume” action button is used to select a new volume dataset. Clicking on it results in a file selection window. The default pattern is “*.v3d”. The volume is
read, displayed (Figure 3.2) and becomes the current 16 bits gray value volume. After a new valid 16 bits gray value volume is given the window with the segment functions is activated.

When the “segment” button is clicked upon, the window labeled with “Segment functions” is placed in front of the other windows as shown in Figure 3.3. The segment functions include all the functions relative to the volume segmentation such as “16->1”, the 16 bits gray value volume will be transformed to both an 8 bits gray value and a segmented volume.

When the “surface” button is clicked upon, the window labeled “Surface functions” is placed on the top of all the windows. The surface functions include all the functions relative to the object surface such as “volume->surface”, this action button gives the possibility to compute the vessel surface on the basis of the 16 bits gray value volume and the segmented volume by the marching cubes algorithm. The surface generation algorithms require an 8 bits gray value volume and a segmented volume with a 0 for tissue and a positive number 1 for the vessel voxels.

The “specials” window labeled “Special functions” is displayed in the same way as the last two windows. The special functions include some particular functions such as histogram function, volume transform function, and branch labeling algorithm.

Figure 3.2 The volume dataset displayed as grey value
Display Control Functions include some user interface objects, which can be used to control the picture in the display window. Such as “display function”, this menu button gives the possibility to select one of the following choices: volume, surface (Figure 4.2), histogram, graphs, and tubes.

Figure 3.3 The window with the segment functions
Chapter 4

Fully automatic branch labeling of voxel vessel structure

Parts of this chapter are extracted from the confidential reference manual.

4.1 Shape parameter extraction of blood vessels

After a contrast agent injection, volume representations of blood vessels acquired by 3D rotational angiography [5, 9] have a clear distinction in gray values between tissue and vessel voxels. Therefore, it is very suitable for diagnosing an aneurysm, a local widening of a vessel caused by a weak vessel wall (see Figure 4.1), or a stenosis, a local narrowing of a vessel caused for example by cholesterol (see Figure 3.2).

Figure 4.1 The grey value image of an aneurysm
4.1.1 The shape parameters of an aneurysm

Physicians may treat an aneurysm by first threading a catheter inside the aneurysm and next deploying coils through the catheter into the aneurysm. Hence they need to know the volume of the aneurysm. In the past users of the 3D Integris system[10] measured the gross volume of an aneurysm by interactively positioning a bounding ellipsoid after which the system counted the number of vessel voxels inside this ellipsoid. The problem is that a small ellipsoid is relatively accurate but difficult to position, and a large ellipsoid is easy to position but relatively inaccurate.

This laborious procedure gave varying results when applied to the same volume by different people. To improve the accuracy and to eliminate the time-consuming interaction, a fully-automatic aneurysm labeling method [11-13] had been developed. The method can be applied only if the aneurysm is wider than the “normal” vessel parts of the volume.

Figure 4.2 An aligned probe (3D image rendered by the marching cube)
4.1.2 The shape parameters of a stenosis

Physicians may treat a stenosis by putting a stent to push and keep the vessel open. Therefore, the length and the cross-sectional shape parameters of the stenosis are important. These shape parameters can be obtained by interactively orienting a plane orthogonal to the vessel by the self-adjusting probe[14]. A probe consists of a sphere, a plane through the center of the sphere and storage for local shape parameters of the vessel. After the probe has interactively been placed on a vessel in the neighborhood of the desired position, the probe automatically adjusts itself such that its plane is orthogonal to the vessel and the center of its sphere is located close to the central axis of the vessel (see Figure 4.2).

However, if two vessel branches are close together as shown in Figure 4.3, where the lower part shows the voxels of a vessel slice currently investigated including the estimated inner and outer circles, while the upper part shows the voxels of a neighbor vessel. It is possible that voxels of the neighbor vessel branch are included in the set of selected voxels which are used to estimate the local shape parameters of the vessel branch investigated. To improve the accuracy a fully-automatic branch labeling method [7] has been developed to give the vessel voxels a unique number (label) per vessel branch (see Figure 4.4). The vessel voxels are displayed in a color according to their label and the surface triangles according to the labels of their vertices.
Figure 4.3 A slice view of a vessel with a neighbor vessel

Figure 4.4 A labeled segmented volume
4.2 Gray level segmentation

The starting point for the fully-automatic branch labeling is a segmented volume (see Figure 4.5 and Figure 4.6). The elements of this segmented volume are signed shorts, with a 0 for a tissue and a 1 for a vessel voxel. This initial segmented volume should not contain tissue inclusions (set of tissue voxels completely surrounded by vessel voxels). The signed short makes it possible to assign different labels to vessel voxels. The labels of tissue voxels are never changed. Negative labels are used to temporarily exclude vessel voxels. To eliminate possible inter- and intra-operator variations, a fully-automatic segmentation method[12] had been developed.

Figure 4.5 An 8 bit segment volume data image
4.3 Outline of the fully-automatic branch labeling method

The fully-automatic branch labeling method consists of five steps (see Figure 4.7). Starting point is a segmented volume (see Figure 4.6). The elements of this segmented volume are numbers with a 0 for a tissue voxel, a 1 for a vessel voxel and a 2 for an aneurysm voxel. The aneurysm labeling algorithm is described in [15]. This makes it possible to assign different labels to vessel voxels during these steps. Vessel voxels with a label 1 are called original vessel voxels. Tissue and aneurysm voxels are never changed. The final outcome is a segmented volume in which all vessel voxels have a label indicating to which bifurcation or branch region they belong to and a set of directed vessel graphs describing the topology of the vessel voxel structures. The flow chart of whole branch labeling algorithm is given in Appendix B.
Figure 4.7 Block diagram of fully-automatic branch labeling
4.3.1 Detection of the extremities

In the first step the wave propagation method of Zahlten [16] is applied to detect the extremities of the vessel voxel structures. Zahlten and others use this wave propagation method to label the original gray value volume and to generate the corresponding vessel graph. Starting with an interactively selected seed voxel as initial Zahlten wave, a new Zahlten wave with the same branch number is created by generating voxel boxes for all 26 corner neighbor voxels of the current wave which were not yet member of any wave.

Next, the current wave is deleted and the new wave becomes the current wave. If the voxels of the current wave are not corner connected, the current wave is split in two or more new waves with each a new unique branch number. Splitting will occur when a wave travels through a bifurcation of the vessel voxel structures. The process is finished when all new waves are empty. The flow chart is described in Appendix B5. The seed points were chosen firstly from the boundary layer of the volume data. These starting points are included in the set of extremities because they are chosen at the far end of a vessel branch. The flow chart of post processing of the extremity detection is given in Appendix B4. After wave propagation starts from these seed points, the smaller blood vessels which are not close to the boundary layer could be also processed. The flow chart is attached in Appendix B2.

The voxels of a wave are given the branch number (label) as can be seen from Figure 4.8, where the voxels are depicted by colored squares corresponding to their label. However the wave propagation method is not accurate enough to detect the bifurcations. As shown in Figure 4.8, the bifurcations 1 and 2 are too late to detect by the incoming waves.

Therefore, the wave propagation method is used to detect the extremities of the vessel voxel structures. When the wave stops to move, in the current wave the voxel with the furthest distance to the seed voxel is selected as the extremity of this branch.
Figure 4.8 Labeling by wave propagation

Figure 4.9 the skeleton of the segmented volume
4.3.2 Creation of the skeleton

After the wave propagation, with the extremities the segmented volume is peeled in a number of iterations as a result the skeleton was created. This skeleton of branches and bifurcations (see Figure 4.9) is a good approximation of the center structure of the vessels.

Starting point is the original segmented voxel with the extremity voxels indicated by a special label. Each iteration starts by labeling the current boundary voxels. Each voxel has at most 6 face neighbor voxels. An original vessel voxel is a boundary voxel if and only if one of these face neighbor voxels is not a voxel with a positive (is > 0) label. The boundary voxels get a label, derived from the local configuration, indicating the priority for peeling. Next, the boundary voxels are removed unless removal would result in a change of topology: one set of face connected positive vessel voxels becomes two face disjunctive sets, or a hole arises. First, the boundary voxels with the highest label are processed. Next, the boundary voxels with a label equal to the highest label minus one are processed. And so on. If a boundary voxel is removed, the labels of its face neighbor boundary voxels are adjusted. Face neighbor boundary voxels with a label greater than or equal to the label of the boundary voxel removed, are immediately processed in decreasing order of their new label.

As shown in Figure 4.9 the darker spots are either extremity or bifurcation voxels. Bifurcation voxels are voxels with more than two positive neighbors in the skeleton.

4.3.3 Creation of the vessel graphs

In the third step the vessel graphs are created. Starting point is the skeleton with the bifurcation voxels indicated by a special label together with the extremities. A directed vessel graph is generated for each set of face connected positive vessel voxels in the skeleton. This vessel graph contains one node for each extremity voxel and one node for each bifurcation voxel. A wave is created and stored in this vessel graph for each skeleton branch between two nodes. This “branch wave” contains a list of voxel boxes (called knots to distinguish them from other voxel boxes) for the face connected positive vessel voxels between these two nodes. Each skeleton branch gets a unique number. The knot voxels get this number as label.
Figure 4.10 The vessel graphs of a segmented volume

Figure 4.11 Node geometry for a bifurcation
The generated vessel graphs facilitate not only fully-automatic vessel tracing from one node to another node of a vessel graph but are also required to label short vessel branches correctly. In this last case information about the bifurcation structure (especially its size) at one end of the vessel branch is needed for labeling voxels at the other end of the vessel branch. The generated vessel graphs contain this neighbor information.

An example of the generated vessel graphs is shown in Figure 4.10. Some of the nodes are visible as black squares. The knot voxels are displayed in a color according to their label.

### 4.3.4 Creation of the node geometry

Correct labeling of voxels requires that vessel voxels inside a bifurcation can be distinguished from vessel voxels outside the bifurcations. To this end node geometry is created. Node geometry contains the position of the skeleton bifurcation, the shape of the bifurcation and the start of its branch regions. Node geometry is also generated for the extremities but this kind of node geometry is not used for final labeling.

First, a center sphere is created. The position of the bifurcation (extremity) voxel is used as center of the center sphere. The radius (in voxels) of the center sphere is derived from the primary distance transform (PDT) values in the neighborhood of the bifurcation or extremity voxel. PDT is the Manhattan distance transform[17] with regard to the boundary vessel voxels.

Next, a branch sphere is created for each skeleton branch. The center of a branch sphere is equal to the position of the knot voxel such that the branch sphere is just separated from the center sphere (see Figure 4.11). The radius of the branch sphere is derived from the genuine PDT values in the neighborhood of the knot voxel of the branch sphere. Travelling along and checking each knot yields the first knot which fulfils these conditions.

Next, one branch and one center plane is created for each skeleton branch. The branch plane is defined by the center of the branch sphere and the normal which is given by the direction of the line from the center of the branch sphere to the center of the center sphere. The position of the corresponding center plane is determined by the intersection of the center sphere and the connection line between the center of the branch sphere and the center of the center sphere. Its
normal is equal to the normal of the branch plane multiplied with -1: the normal of the branch plane and the normal of the corresponding center plane point at each other.

Finally, to reduce the rather large center regions, the branch spheres, the branch planes and the center planes are moved to the center of the center sphere keeping the branch regions on its own vessel branch.

The node geometry of a bifurcation is not only used in the final labeling step but also to check whether the bifurcation is caused by a small lateral vessel branch connected to a main vessel branch, by a number of small vessel branches connected to a wide vessel branch (dominant branch bifurcation) or by a connection of three or more roughly equal vessel branches. In case of a main branch bifurcation, it is possible to give the vessel voxels of the two main vessel branches and the vessel voxels inside the bifurcation the same label. In case of a dominant branch bifurcation, it is possible to give the voxels inside the bifurcation the label of the wide vessel branch. In case of a small lateral vessel branch, node geometry is used to check whether the corresponding skeleton branch is an unwanted skeleton branch which should be removed.

An example of a set of node spheres is shown in Figure 4.12. The cyan spheres are the center spheres, the magenta spheres are the branch spheres. The branch spheres of the extremities are not displayed. The knot voxels are displayed in a color according to their label (this label is assigned in the fifth step).

Note the occasional overlap of center and branch spheres, caused by very short vessel branches.

4.3.5 Assignment of the final labels to the vessel voxels

In the fifth step the vessel voxels get their final label. First, the voxels in the branch regions (see Figure 4.13) get the label of their skeleton branch. Next, the voxels in the center regions get the label of the center region. Finally, the vessel voxels between two branch regions get the label of their skeleton branch. A branch region is the set of voxels, face connected to the knot voxel of the branch sphere, between the branch plane and the corresponding center plane.
Figure 4.12 The node spheres of a segmented volume

Figure 4.13 Open branch region
A center region is the set of voxels, face connected to the center voxel of the center sphere, between the branch regions. An example of a labeled segmented volume is shown in Figure 4.8. Figure 4.14 is an example of a labeled segmented volume after reduction of the center regions.

The label of a center region depends on the bifurcation type. In case of a dominant or main branch bifurcation the label of the center region may be equal to the branch number of the wide or main vessel branch (see previous section). Else, the center region gets a unique label, different from all branch numbers.

Figure 4.14 A labeled segmented volume with small center regions
Chapter 5

Faster detection of extremities by wave propagation

In order to speed up the extremity detection procedure, two methods are given in this chapter. One is a down sampling method, which resizes the original volume to a smaller volume. The computation time, based on the smaller volume should be shorter than the original used. Another method is wave propagation on the surface of blood vessels, which means not all the voxels are processed in the original algorithm, only the voxels on the surface of the blood vessels are the input data.

5.1 Down sample analysis

Down sampling or sub sampling is the process of reducing the sampling rate of a signal in signal processing. It is used to reduce the size of the data in image analysis. A faster detection algorithm is needed to find the extremities in the segmented volume, so the down sampling is used to resize the original segmented volume to a smaller volume by combining 2*2*2 original voxels to one new voxel.

5.1.1 Methods of down sampling in 2D

There are two simple ways to combine the eight original voxels to one new voxel. The voxels of such a smaller volume can be the minimum or the maximum of the corresponding voxels in the original segmented volume.

The value of the new voxels is a function of eight original voxels, which is expressed in an equation:

\[ n_{i,j,k} = F_1(\{o_{p,q,r}, p \in \{2i,2i+1\}, q \in \{2j,2j+1\}, r \in \{2k,2k+1\}\}) \]  \hspace{1cm} (5.1)

In this equation \( \{p, q, r\} \) indicate the ordinate in x, y, z axis respectively. \( \{o_{p,q,r}, n_{i,j,k} \in \{0,1\}\} \) indicates the original voxel value and the new voxel value respectively.

In order to simplify the problem, the domain of function \( F_1 \), which consists of eight numbers (0
or 1) as eight dimensions space, is introduced and the eight dimensions space is transformed into one dimension space.

The sum of 8 original voxels is expressed as

\[ S_{i,j,k} = \sum_{p=2i}^{2i+1} \sum_{q=2j}^{2j+1} \sum_{r=2k}^{2k+1} o_{p,q,r}, \{S_{i,j,k} \in \{0,1,...,8\}\} \]  

\[ n_{i,j,k} = F_2(S_{i,j,k}) \]  

The domain of function F2 consists of nine numbers \(\{0,1...8\}\) as a one dimension space. It is wise to set F2 to be a monotonous non-decreasing function. That means: if the sum of the voxels of the original volume is greater the new voxel should be also greater or equal. Then the new voxel value can be determined by the threshold \(T\), \(\{T \in \{0,1,...,8\}\}\). \(n_{i,j,k}\) has nine possibilities according to the threshold \(T\) in equation (5.4) as follows:

\[ n_{i,j,k} = (S_{i,j,k} \leq T) \, \equiv \, 0 : 1 \]  

Firstly three cases are discussed in this section.

1. The threshold \(T\) is set to 7 so that \(n_{i,j,k}\) is the minimum of \(S_{i,j,k}\). With \(n_{i,j,k}\) and \(S_{i,j,k}\) replaced by the formula. It can preserve the separation between blood vessel segments;

2. The threshold \(T\) is set to 0 so that \(n_{i,j,k}\) is the maximum of \(S_{i,j,k}\). With \(n_{i,j,k}\) and \(S_{i,j,k}\) replaced by the formula. Preserving the blood vessels as much as possible;

3. The threshold \(T\) is set to 4. Keeping the separations or blood vessel segments. The solution is attached in the Appendix A.1.

In this project, the down sampling method has been implemented according to case 3. The value \(T\) just was set as 4 simply to preserve the separation between the blood vessels.

### 5.1.2 Methods of down sampling in 3D

Firstly the definition of an extremity is discussed here. Euclid has just defined points, and stated that the extremities of lines are points[18]. In this paper, the false extremity and the real extremity should be given based on mathematical morphology. Their definitions can be used by the check procedure later.

**Definition of a real extremity:**
A real extremity is a point to indicate the distal or terminal portion of a structure, and on the elongation of the object center line. In mathematic morphology the extremity at least has one face connected neighbor as background which value is 0, that means it is a point on the object surface.

**Definition of a false extremity:**
A false extremity is a point that does not connect to the distal or the terminal portion of a structure. And it is not a point at the tip of a branch or on the object surface. However in this project, the result of the original algorithm is considered as the ground truth. Hence a false extremity is the extremity that cannot be detected from original volume but can be found from the new volume after down sampling. A lost extremity is the extremity that can be detected from original volume but cannot be found from the new small volume after down sampling.

The situation in 3D is more complex than the situation in 2D. Although the down sampling algorithm decreases the size of a segmented volume, the small blood vessels are removed, which consist of single voxel, resulting in lost extremities. The details of the down sampling algorithm are discussed in Appendix A.2.

![Figure 5.1 The comparison result. The left image: the original volume, the right image: the down sampled volume](image-url)
5.1.3 **Down sampling methods analysis**

One of the advantages of the “minimum” volume is preserving the separation between the vessel segments. The disadvantage is that two connected vessel segments may be separated, resulting in false extremities, or even worse, that complete vessels segments may be lost, resulting in lost extremities. Using “maximum” volume can preserve all the vessel segments, even small blood vessels. However, two separated vessel segments may be connected, resulting also in lost extremities.

Whether the lost extremities present a problem for the clinical volumes is not clear. A possible approach is that the original extremity set can be seen as the ground truth. The false extremities and the lost extremities can be found from the new extremity set. Some possible cases in 2D are discussed in Appendix A.4. A general model was created which includes three blood vessels (the black grids in the graphs) with different shape, close to each other. The processing can be seen from the graph in Appendix A.3.

![Image](image.png)

Figure 5.2 The comparison result. The lost extremities displayed as the yellow points, the false extremities displayed as the blue points
5.1.4 Comparison method of the two extremity sets

The down sampling method is used to decrease the dataset size to speed up the extremities detection. Due to the disadvantages of the down sample method, some extremities are missed and some extremities are not at the tip of a blood vessel branch. It is necessary to develop a test approach to figure out the false extremities and the lost extremities from the two extremity sets. This method was described as pseudo-code and is attached in Appendix A.5.

Table 5.1 The comparison between the original and down sampled volume

<table>
<thead>
<tr>
<th>Datasets</th>
<th>Old / New volume</th>
<th>False/Lost extremities</th>
<th>Improved ratio</th>
</tr>
</thead>
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<td></td>
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<td></td>
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<td>81/58</td>
<td>50 / 27</td>
</tr>
</tbody>
</table>

5.1.5 Result and discussion

The down sampling method is implemented in this project and an example of the result image can be seen in Figure 5.1. The original volume data size is 128×128×128 as the left image in Figure 5.1, the new volume after resizing is 64×64×64 as the right image in Figure 5.1. We tested 60 datasets with different size for the extremity detection method. The wave propagation algorithm runs faster than based on the original volumes. As a result, the processing speed is increased. But the detection accuracy of the extremity needed to study. Hence two sets of the
extremities (one was detected from the original volume, another was detected from the downsampled volume) have been compared, and described in Appendix A.5.

According to the definition of the false and the lost extremities as mentioned in section 5.1.2, the comparison result is given in table 5.1. Although using down sampling improved the processing speed, some small branches are missed. As a result the extremities are lost on these branches.

5.2 Surface wave propagation

The main algorithm for detection of the extremities is the wave propagation through the vessel voxels of the segmented volume. The computing time depends mainly on the generation of a new wave from the corresponding old wave. The surface wave propagation is implemented. The wave is moved along the blood vessel surface. Only the surface vessel voxels were processed, the voxels in the inner blood vessels were not involved in the computation even accessed. According to the definition of the extremity, the extremity should be found on the vessel surface. Therefore the extremity detection could not be effected by excluding inner vessel except that those extremities found in the six boundary layers. Since there the final extremity voxel is an inner voxel not a surface voxel. As a result, the extremity detection procedure could be finished more quickly than before.

Next, the problem is whether the set of extremities detected with this new algorithm corresponds to the set of extremities found with the original wave propagation algorithm, which means the number of extremities should be the same and the extremity voxels should be located in the same position on the branch tip between the new and the original algorithm.

5.2.1 Moving on the blood vessels surface

Suppose that the cross section of blood vessel is like a disk. The surface voxels consists of a circle, the edge of the disk. Therefore the saving time on the section area can be estimated simply by equation 5.5.

\[
T_s = \tau(\pi \cdot r^2 - 2\pi \cdot r) = \tau \cdot \pi \cdot r(r - 2)
\]  
(5.5)
τ is computation time needed by each voxel.

Ts indicate the saved computation time between the new wave propagation and original method. The computation time can be evaluated using equation 5.5. The surface wave propagation cannot be faster than the original wave propagation on processing the small blood branch which radius is smaller than 2 voxels.

![Figure 5.3 The surface wave propagation moving on the surface of the blood vessel](image)

Actually, in the initial steps of the wave propagation in Appendix B.3, the initial wave was filled by the surface voxels. The surface voxels selection can be done during the already present component labeling procedure. The approach is described in Appendix B.5. During the generation of the new wave, finding all the neighbors of the old wave, in their neighbors only the surface voxels would be put into the new wave as shown in Figure 5.3. The “condition” in Appendix B.5 includes the procedure to determine whether a voxels is a surface voxel.

### 5.2.2 The seed voxel detection

Wave propagation yields the best results, if the wave could simulate blood flow to travel from the wider to narrower vessels. The seed voxel should be in the neighborhood of the extremity. Generally, the large dominant vessel structures start on the boundaries of the volume with their widest vessels. The center voxels of the widest vessel can each be considered as a seed point.

It is however possible to find some vessels which cross sections at the boundary layers. Then the center point can also be calculated by those edge voxels which belong to a cross section. Hence the seed selection could be speeded up since only the edge voxels would be accessed. These center points labeled with the diameter of the cross section are put into a seed wave. The
elements in the seed wave should be sorted according to the label. The first element with the biggest diameter is selected as the seed voxel. The seed selection method is developed and described as follows.

1. From the boundary layers to search the edge voxels. The edge voxel has at least one neighbor belonging to tissue.

2. A trace method can be used to find all the edge voxels which belong to a cross section. It starts with an edge voxel, and then finds all the edge voxels from its 26 neighbors. This procedure could be carried out in a number of iterations until all the edge voxels are included in the edge wave.

3. Generally, these edge voxels in an edge wave compose a circular shape. Therefore the center point and the diameter of this circle can be calculated. These center voxels are labeled and sorted by the diameter in a seed wave.

4. The last three steps could be carried out in a number of iterations until there is no edge voxel left at the boundary layers.

At last, the center voxel labeled with the biggest diameter is selected as the seed point, and its edge voxels are considered as the initial wave.

5.2.3 The extremity detection

In the fully-automatic branch labeling algorithm [7], the wave consists of voxels which mostly form a cross section of the blood vessel. When the wave moving stops, a voxel could be found from the final wave, its distance to the start voxel (the seed points) is the farthest. This voxel can be saved into an extremity set as an extremity.

However in the surface wave propagation, the wave always consists of the surface voxels. Obviously, the center of the stop wave should be at the extending line of this branch. Therefore, a possible solution is to set the center voxel as the extremity for this branch. This method is implemented and the result is shown in Figure 5.4. There are two points at the branch tip in the right corner of the image, and the blue point indicates the center of the final wave: the new extremity.
In Figure 5.4 the yellow points indicate the extremities which are detected by the volume wave propagation; the blue points indicate the ones which are detected by the surface wave propagation; the pink symbol denotes the extremity pair position at the same voxel.

A false extremity would be detected by the original method when a cycle is present in the segmented voxel volume. In such a case the extremity is not detected at the branch tip. A yellow point labeled with "lost extremity" can be seen on the cycle in Figure 5.4. A simple approach can solve this problem, which is to check whether all neighbors of the stop wave are tissue voxels. If any neighbor voxel has a different branch number from the stop wave, the extremity selection procedure would not be started. As a result no false extremity would be detected.

Figure 5.4 The comparison between the original and the surface wave propagation. The yellow points indicate the old extremities. The blue points indicate the new extremities.
5.2.4 The validation of the surface wave propagation

There are two extremities sets which are detected by the volume and the surface wave propagation. The detection result of the original method is regarded as the ground truth. Not only the amount but also the positions of the extremities are compared between the two data sets.

In this section, the definitions of the lost and false extremity are similar to the definition in section 5.1. A false extremity is defined as the extremity in the new extremity set created by the surface wave propagation, which cannot be found in the old extremity set, the ground truth. A lost extremity is the extremity in the old extremity set, which cannot be found from the new set. The extremity pair consists of the old and new extremity at the same branch tip. The relationship between the old extremity set and the new extremity set is described as the graph in Figure 5.5.

![Figure 5.5 The graph of the false and the lost extremities](image)

Some extremities pairs are close to each other, and they can be recognized simply. Some extremities pairs are not close to each other, for example the old extremity detected on the branch boundary and the new extremity found on the branch centerline. But it is possible that a 26 connected path may exist between these two extremities.
At the same branch tip, the extremity positions might be different between the two detection methods. A comparison method is developed to recognize the extremity pair at the same branch tips and is described as follows.

1. From the two lists extremities to find the extremities pairs using the distance threshold, for instance 2 voxels units.
2. To find the extremities pairs which distance are greater than the distance threshold and smaller than the diameter of the corresponding branch.
3. From one extremity try to trace a 26 connected path connect to another extremity as close as possible to the straight line between these two extremities.

The comparison result is shown in Figure 5.7. All the extremities pairs are indicated as pink symbol, the blue part indicates the path between the old and the new extremities, the yellow symbol indicates the lost extremities.

A validation method is needed to test the comparison method. Set two probes corresponding to the two voxels in OpenGL view, and test whether the function find path can find a 26 connected
path between them. The result can be seen in Figure 5.6, the blue part represents the path between the two probes.

Figure 5.7 The original extremity set and the new extremity set

5.3 Result and discussion

We used 60 datasets to test the surface wave propagation. The size of the data ranged from 128×128×128 to 256×256×256. Compared to the volume wave propagation, the computation time is decreased at least 24% and at most 82%. Parts of the validation results are given in table
5.2. The size of the first three images is 128×128×128 and the size of the last three images is 256×256×256. The extremity amount, the elapsed time and the amount of the false/lost extremity are given in the column "Extremity", "Elapsed" and "False/Lost extremities" respectively in table 5.2. The former numbers in each grid in these three columns belong to the volume wave propagation. The latter numbers are calculated based on the surface wave propagation. The unit of the elapsed times is in second. Compared to Figure 5.7, an example of the result image is shown in Figure 5.8. All extremity pairs are found and indicated as pink symbols.

Figure 5.8 The final comparison result of the volume and surface wave propagation. The extremities pairs are displayed as pink points with the blue paths on the surface
Table 5.2 The comparison between the volume and the surface wave propagation

<table>
<thead>
<tr>
<th>Datasets</th>
<th>Old / New method</th>
<th>Lost/False extremities</th>
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<td>Large_ane02</td>
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Chapter 6

Improved automatic blood vessel branches labeling

6.1 Related work on branch labeling

The topology of the blood vessels can be represented by the graph structure, which is generated by various skeletonization algorithms. Skeletonization methods based on morphological thinning are presented in [19, 20]. The topology conditions resulted occasionally in small cycles not present in the segmented voxel volume in the thinning method of Bertrand et al [19].

A single skeleton is directly generated from the gray value volume [20]. However this method cannot be used for separated components. Since the vessel voxels cannot be labeled according to the branch or center region they belong to.

Skeletonization algorithms based on distance transformations are described in [21, 22].

Skeletonization algorithms based on thinning and distance maps are presented in [23, 24].

Skeletonization algorithms based on wave propagation are described in [25]. A system for reconstruction of a vessel tree is created by a wave propagation in [26]. The wave propagation method of Zahlten labels the original gray value volume using an appropriate threshold and generates the corresponding vessel graph. However this method is not accurate enough at the junctions (bifurcations), see Figure 4.8.

A method for robust and objective decomposition and mapping of bifurcating vessels is presented in [27]. But a 3D triangle surface model of the vessel boundaries is needed as input for their computations. A thinning method is used after a wave propagation in [7]. A segmented voxel volume with the extremities is set as the input data; it is peeled in a number of iterations. The resulting skeleton of branches and bifurcations is a better approximation of the vessel graph than the method of Zahlten. However the thinning is a time consuming approach for the bifurcation position correction.
6.2 The center lines extraction algorithm

Skeletonization algorithms are mentioned in section 6.1. In this paper, the surface wave propagation is used to not only detect the extremity but also to extract the centerlines and bifurcations.

During the propagation of the wave, a wave and its center voxel are labeled by a branch number. All waves and their center voxels are stored in a wave set and a center voxel set respectively. A center voxel structure is created which includes a branch number, a wave index in this branch and the wave diameter.

The center and the normal of a wave are important for the adjustment of the wave moving direction. And the plane (where a wave lies on) should be orthogonal to the vessel whose shape has to be measured. An oblique plane would give the wrong parameters such as diameter.

6.2.1 The wave plane normal

This section describes a method of fitting a plane to uncertain three-dimensional (3D) data. The range data is given as a set of 3D points \( \{ P_i = (x_i, y_i, z_i) \} \). All data points \( P_i \) that lie on the plane defined by the normal \( n = (A, B, C) \) and the perpendicular distance to the original \( d \) satisfy the equation 6.1

\[
    n \cdot P_i - d = Ax_i + By_i + Cz_i - d
\]  

Figure 6.1 A normal of plane (from www.mathworld.com)
In reality however, not all data points lie exactly on the plane, hence the value $\varepsilon$ is introduced on the right of equation 6.2 standing for the fitting error:

$$Ax_i + By_i + Cz_i - d = \varepsilon_i \quad (6.2)$$

The plane normal $n$ gives the following homogeneous least square problem:

$$N \cdot n = [0 \quad 0 \quad 0]^T \quad (6.3)$$

With

$$N = \begin{bmatrix}
\sum_{i=1}^{N} x_i^2 & \sum_{i=1}^{N} x_i y_i & \sum_{i=1}^{N} x_i z_i \\
\sum_{i=1}^{N} y_i x_i & \sum_{i=1}^{N} y_i^2 & \sum_{i=1}^{N} y_i z_i \\
\sum_{i=1}^{N} z_i x_i & \sum_{i=1}^{N} z_i y_i & \sum_{i=1}^{N} z_i^2
\end{bmatrix} \quad (6.4)$$

The solution is given by the null space of the matrix $N$. This null space is computed by means of a singular value decomposition (see section 2.6 of [28]). In the same way, a least-square ellipse is directly fitted through a number of 3D points in a wave. As shown in Figure 6.2, a yellow center and a green fitted ellipse indicate a wave.

Figure 6.2 A wave fitted by an ellipse
6.3 The bifurcation detection

Generally, bifurcations can be found when the wave is separated to two or more new waves. Two specially designed probes can be used to simulate the bifurcation detection by the surface wave propagation. Such a probe (see Figure 6.3) consists of a sphere and a plane through the center of the sphere [14]. An example is shown in Figure 6.4 waves are indicated by ellipses with a green path between two probes. The bifurcations are found where the ellipses disconnect each other.

Figure 6.3 A probe traces to another probe

Two main types of bifurcation are defined in this paper. When the wave moves from a wider vessel to two (or more) narrower vessels, the wave can be disconnected. Where such disconnected waves are found, we called it the type I bifurcation position. Conversely, when the wave moves from a narrower vessel to a wider vessel, we call the location with the disconnected waves a type II bifurcation.
As mentioned in section 6.1, in some cases the wave propagation is not accurate enough at the bifurcation. This problem can be solved by an 'abnormal wave' detection method. Three parameters of every wave in a branch can be found from the corresponding center voxel in the center voxel set (see section 6.2). When a wave diameter increases sharply, this wave can be labeled as an abnormal wave. All waves from this abnormal wave to the disconnected wave should be labeled as the bifurcation wave. The flow chart of this solution is given in Figure 6.5.
This method is developed and the steps of the algorithm are described as follows. An example of this approach result image is shown in Figure 6.6

1. Surface wave propagation is started from the initial wave, and all parameters of a wave are calculated and stored.

2. The wave is labeled and a center voxel structure is created. The wave parameters are used to adjust the moving direction. In the mean time, the abnormal wave is detected by a threshold.
3. When the wave is disconnected, a bifurcation would be labeled as type I or II according to the abnormal detection result. The center voxel of the old wave could be set as the bifurcation position.

4. For the bifurcation type I, if the diameters of the two or more new waves are similar, all new waves could be labeled by the new branch number. Otherwise, if one of new waves which diameter is similar to the old wave and has a bigger a threshold than the other, this wave should be labeled as the current branch number and the other should be labeled as a small branch (see Figure 6.7).

5. A bifurcation structure is created and it includes three labels, a father branch number, a left son branch number and a right son branch number.

Figure 6.6 A result image of the bifurcation detection
Figure 6.7 The bifurcation labeling result. The gray parts indicate the bifurcation type II and the yellow symbols indicate the bifurcation position.
Chapter 7

Result and validation

7.1 Surface wave propagation

The surface wave propagation has been applied for fully-automatic branch labeling algorithm to 60 clinical volume datasets (15 of them with a resolution of 256×256×256 voxels, the rest 128×128×128 voxels), acquired with the 3D Integris system. The voxel size varies between 0.2 and 1.2 millimeter. Examples are shown in Figure 7.1 and Figure 7.2. The amount and the positions of the detected extremities by the surface and the volume wave propagation are same. The final labeling results are quite similar between these two methods.

Figure 7.1 The final labeling result based the original wave propagation
After the extremities are detected, the segmented volume with the voxels labeled as the extremity is used by the last four steps as input data. The extremity positions are checked again in the third step which creates the vessel graph according to the centerlines and bifurcations. Using the validation algorithms is described in Section 5.2.4, for most cases, there is nearly no different branch labeling result between the surface and the volume wave propagation.

Figure 7.2 The final labeling result based the surface wave propagation
7.2 Bifurcation detection

We tested 6 datasets for the bifurcation detection. In this case, as the bifurcation definition and the labeling method are different from the original method, it is hard to compare the results of the two methods. The dark parts in Figure 7.3 indicate bifurcations which are labeled by the original method. Almost all these bifurcations can be detected by the detection method, and they can be found in Figure 7.4 where they are indicated by the yellow symbols.

After the extremity detection, the centerlines and bifurcations extraction by the surface wave propagation, the extremities, center voxels and bifurcation structures have been created and labeled by the branch number. These data structures are sorted and stored in three data sets which can be used to create a vessel graph. The vessel graph generation method is described as follows.

1. Based on the center voxels set, the seed point and the first center voxel which has the same branch number can be connected by a 6 connected path.

2. All center voxels which belong to a branch could be connected each other. Then the last center voxel is connected to the extremity with the same branch number.

3. If there is no an extremity with the same branch number, a bifurcation can be connected with three branches, a father branch, a left son branch and a right son branch.

4. A vessel graph could be created until the extremity set, the center voxels set and the bifurcation set are empty.

Because of the time reason, the new vessel graph is created by this method has not tested and compared with the original vessel graph.
Figure 7.3 The bifurcation labeling result by the original algorithm.

Figure 7.4 The bifurcation labeling result by surface wave propagation with the correction.
Chapter 8

Conclusions and future work

8.1 Conclusion

In this thesis, firstly a fully-automatic branch labeling method is introduced, which has been developed by Bruijns [7]. It can extract the shape parameters of the diseased vessel parts from a volume representation. Secondly we discussed and analyzed the blood branch labeling acceleration algorithms, and proposed two methods for improvement. The first one is called the surface wave propagation method which restricts the wave moving only along the blood vessel surface. The second one combines a thinning algorithm with the surface propagation to extract the center lines and the bifurcations of the blood vessels.

Proper validation results are given in this paper. The volume wave propagation is replaced by the surface propagation and put into the original branch labeling algorithm. For most cases, there is nearly no different branch labeling result between the surface and the volume wave propagation. During the extraction of the centerlines and bifurcations based on the surface wave propagation, the branch labeling procedure is also implemented. Almost all these bifurcations can be detected by the detection method. The result shows that the two methods can substantially decrease the computation time and keep the labeling accuracy. However, the centerline extraction method has not tested so far due to the time limitation. Whether the branch labeling result, generated by surface wave propagation based on a vessel graph, are suitable for computer assisted diagnosis has not been investigated yet.

With these characteristics in mind we present four contributions of our work,

1. A study of the down sampling method to detect the extremity is implemented and discussed both in 2D and 3D. The conclusion is that the down sample method is not suitable for the extremity detection.
2. A surface wave propagation algorithm is developed to detect the extremities. The validation result shows that the procedure is speeded up and the detection accuracy is preserved.

3. The surface wave propagation algorithm is also used to extract the centerline and the bifurcation. The tested result shows that it can find the bifurcation more accurate than the volume wave propagation based on our bifurcation correction method.

4. A new vessel graph creation method in introduced in this paper. All above methods are implemented in C++ in the demo program, v3d_main.

The following conclusions can be drawn from the results, the figures and the experiences gathered during testing:

1. Surface wave propagation gives always correct and visually acceptable extremity detection results. The comparison result with the volume wave propagation shows that the detection time is decreased by at least 24% and at most 82%.

2. The centerlines and bifurcations extraction by surface wave propagation gives correct and visually acceptable results.

3. Based on the extremity set, the center voxels set and the bifurcation set, the vessel graph is created and it needs to be evaluated.

4. Whether the branch labeling result, generated by surface wave propagation based on a vessel graph, are suitable for computer assisted diagnosis has not been investigated yet.

### 8.2 Detection function

Although encouraging results have been obtained, many things can be improved.

1. First of all, the seed point selection is implemented successfully in the 6 boundary layers. But the seed points found from some isolated blood vessels did not proved to locate at the branch tip. Because these small blood vessels do not close to the boundary layer, the initial wave created based on these seed points in such a case could not be a fitted ellipse which is cross section of the current blood vessel.
2. Secondly, the direction adjustment is dependent on the normal of the current wave. As a result, the wave normal cannot be accurate when the waves travel through a bifurcation. Because the situation is very complicated in the bifurcation area. It is hard to fit the current wave as an ellipse. This is the same problem meet with the wave propagation method of Zahlten.

3. Thirdly the geometry center of a bifurcation is not given in this project. It is still a hard problem to calculate the geometry center of the blood vessel bifurcation. We also did not investigate whether the bifurcation detection method in this report is better than others.

4. At last but not least the vessel graph creation method is too simple in this project. There are many things which can be improved.
Appendix A

Down sampling discussion

A.1 Down sampling method

Down sample approach is discussed in chapter 5, the problems and the possible solutions are discussed only in 2D. As mentioned in section 5.1, there are three cases being discussed.

In case 3 if the sum is less than T which means there are less than 4 object voxels (belong to blood vessel, value is 1) in current 8 original voxels, the new voxel value $n_{i,j,k}$ can be defined as 0 (background); if the sum is over than T which means there are more than 4 object voxels in current 8 original voxels, the new voxel value $n_{i,j,k}$ can be defined as 1. But when the sum is equal to T the situation is too complex to define the new voxel value. Hence this problem could to be discussed in space (3×3×3), which is bigger than now (2×2×2). The neighbors of the current 8 original voxels need to be taken into account. The sum of 27 original voxels is expressed as

$$S_{i,j,k}^n = \sum_{p=2i}^{2(i+1)} \sum_{q=2j}^{2(j+1)} \sum_{r=2k}^{2(k+1)} o_{p,q,r}$$

(A1.1)

The sum of the neighbors of the 8 original voxels is

$$S_{i,j,k}^x = S_{i,j,k}^n - S_{i,j,k}$$

(A1.2)

Another threshold is needed for $S_{i,j,k}^x$

$$x = (S_{i,j,k} < T)?0:((S_{i,j,k}^x < T^x)?0:1)$$

(N is the dimension of image)

(A1.3)

In order to simplify the problem, this solution is discussed in 2D. The value of the new voxel is defined by threshold T. Here the T is defined as 2, so the new value is:

$$n_{i,j} = (S_{i,j} \leq 2)?x:1$$

(A1.4)

$$x = (S_{i,j} < 2)?0:((S_{i,j}^x < T^x)?0:1)$$

(A1.5)
\[ T^x = \text{Floor}\left(\frac{\text{neighbors} + 1}{2}\right) \]  

(A1.6)

Three situations has been taken into account according to the value of \( S_{i,j} \):

1. To set the new value as 0 (background) when \( S_{i,j} \) is less than 2
2. To set the new value as 1 (object) when \( S_{i,j} \) is over 2.
3. \( S_{i,j} \) is 2, the neighbors of 4 original voxels should be checked whether they were face connected each other, \( S^x_{i,j} \) is considered. If \( S^x_{i,j} \) is over 2 so the new voxel value is set as 1 because these original voxels are face connected with others. Otherwise the new value set as 0.

This method is described as pseudo code as follow:

**Function Down_sample ()**
/*From the left upon corner to process the original segmented volume by loop*/
/*From 1\textsuperscript{st} row start to down sample */

For \( i = 1 \) to 1
/*from 1\textsuperscript{st} column to start */

For \( j = 1 \) to 1
/*If most of voxels are background so set the new voxel as background*/

Case 1: If \( S_{i,j} < 2 \) then set \( N(u, v) = 0; \)
/*If most of voxels are object so set the new voxel as object*/

Case 2: If \( S_{i,j} > 2 \) then set \( N(u, v) = 1; \)
/*if the detector lies at the edge of object*/

Case 3: If \( S_{i,j} == 2 \) then
/*shift right to one column until there no new column*/

If \( S^x_{i,j} > 2 \) then set \( N(u, v) = 1, \)
/*if current detector lies at one single voxel blood vessel*/
Else set \( N(u, v) = 0; \)
End if
End if
End for j
End for i
End Function
A.2 Down sampling analysis in 3D

A new hybrid algorithm is discussed which includes both extremity detection and down sampling in this section. Firstly using the down sample method to resize the original segmented volume to a smaller volume, computing time will be saved because the current volume size is an eighth of the original segmented volume. And then the extremities of wider blood vessels which consist of more than 2 voxels have been detected by wave propagation in the down sampling segmented volume.

Secondly, a method of false extremities detection can be developed to remove the false extremities which were detected in the down sampled segmented volume because some blood vessels may be merged during down sampling. One approach to remove the false extremities is to check every extremity in the original segmented volume according to the definition of extremity.

At last, the wider blood vessels are labeled and then removed from the original segmented volume, which means to set those wider vessels voxels value as 0 (background), the narrow or small blood vessels which consist of less than 2 voxels are left in the original segmented volume. The wave propagation method can be used again to detect these small blood vessels after adjusting the volume boundary according to the left object in it. It is possible that some narrow blood vessel structures starts on the new boundaries of the smaller volume.

This hybrid algorithm can be described as pseudo-code and was attached in the Appendix A.3. The comparison is given as follow:

The advantage of the Hybrid algorithm:

1. Using the down sampling to create a smaller volume to detect the extremities, as a result whole processing is speeded up;

2. The extremities detected from the wider blood vessels will not be effected by the down sampling;
3. The extremities of small blood vessel segments in the original segmented volume may be detected in the smaller volume, there is no blood vessel lost and more extremities may be detected.

The disadvantage:

1. It is possible that some false extremities still exist.

2. It is possible that some narrow blood vessels may be merged with the wider one close to each other because of the down sampling. As a result, some narrow blood vessels still cannot be labeled due to the lost extremities.
A.3 The pseudocode of the extremities detection function

Function Detect_Extremities ()

/* First step is to down sample the original segmented volume */

DownsampledVolme = Downsample (OriginalVolume);

/* Use double wave propagation method to detect the extremity from the down sampled volume */

ExtremitiesofWiderVessels = DoubleWavePropagation (DownsampledVolme);

/* remove the false extremities from the list by the detection approach */

ExtremitiesList = DetectFalseExtremities (ExtremitiesofWiderVessels);

/* According to the extremities list to label the blood vessels and remove the wider blood vessels from the segmented volume, then reset the boundary of the segmented volume */

SmallVolume = Branching (ExtremitiesList);

/* Use the double wave propagation method again to detect the extremity of the small blood vessels in the small volume */

ExtremitiesofSmallVessels = DoubleWavePropagation (SmallVolume);

End Function
A.4 Down sampling analysis in 2D

As mentioned in section 5.1.3, four situations are discussed here. The black block indicates the blood vessel and the white block means the tissue or background. A letter “e” in a block indicates the extremity. From left to right and from up to down, every four original voxels has been processed and created to one new voxel in a new segmented volume. The situation 2 and situation 3 are the result after shift situation 1 right to one column and shift down to one row respectively. In situation 4 three blood vessels do not close to each other.

1) Situation 1 Three blood vessels close to each other, the processing starts from the object edge.

Original segmented volume

New smaller volume after down-sampling
2) Situation 2 Blood vessels close to each other; the processing does not start from the edge of object.

3) Situation 3 Shift one row up to the case 1.
There are four situations used to compare the three down sampling methods. Here using average as the threshold can get better result in situation which similar to these four cases. Due to the time limit, other complex situations do not discuss in this project.
A.5 The pseudocode of the extremities comparison Function

This comparison function can be used in section 5.1.4 to figure out the false and lost extremity between the original extremity list and the down sampling extremity list. It also can be used for comparison of the original and the surface wave propagation. The parameter bonsurface is the switch.

Function Compare_Extremities (original_list, new_list, bonsurface)
/*Compare two extremities lists to give the false and the lost extremities, bonsurface True for surface wave propagation; False for downsampling */
For i=1 to length (original_list)
    For j=1 to length (new_list)
        /*Calculate the distance between every pair of neighbor extremities from the two lists and find the pairs which distance less than threshold, for instance 2 voxels units*/
        If (original_list(i) – new_list(j)) < distanceThreshold - bonsurface then
            /*find the voxels corresponding to extremities and mark them*/
            Old_mark(i) = new_list(j);
            New_mark(j) = original_list(i);
        End for j
    End for i
If (TRUE == bonsurface) then
    /*find the pairs of extremities which distance less than diameter of the widest blood vessel*/
    For i=1 to length (original_list)
        If (NULL == Old_mark(i)) then
            For j=1 to length (new_list)
                If (NULL == New_mark(j)) then
                    If (original_list(i) – new_list(j)) < biggestDiameter then
                        /*find the voxels corresponding to extremities and mark them*/
                        If (TRUE == FindPath(original_list(i), new_list(j))) then
                            Old_mark(i) = new_list(j);
                            New_mark(j) = original_list(i);
                        End if
                    End if
                End if
            End for j
        End if
    End for i
End if
End Function

Function FindPath (voxelA, voxelB)
/*Try to find a 6-connected path between two voxels*/
While (path < biggestDiameter)
    /*From voxelA grow toward to voxelA along the vector between the voxelA and voxelB*/
    (Neighbors, path) = RegionGrow (voxelA, voxelB)
    /*If voxelA can be find from the list Neighbors then return TRUE*/
    If voxelB IsExist (Neighbors) then
        Return TRUE
    End if
End while
Return FALSE;
End Function
Appendix B

Fully-automatic branch labeling

B.1 The flow chart of wave propagation

1. Start to detect the extremity
2. Initial setting: 2.1 Clear all extremities; 2.2 Set volume01 value;
3. Clear all seed points 3.1 and 3.2 Find the local max in the boundary layers;
4. Initial propagation wave set; Clear all waves
5. Find initial vessel voxel (seed points)
6. Label the component?
   - Yes/True
     - Re-label vessel voxels of small components to tissue voxels (B.2)
   - No/False
     - If condition
       - !ane_neighbour && nr_voxels < min_nr_voxels
8. Move waves and display components (B.3)
9. Post processing after the extremity detection
10. End
B.2 Relabel vessel voxels of small components to tissue voxels

Start

Removed components Nr ++

In component box to re-label vessel voxels of small components to tissue voxels

If (!trial_waves)

Remove possible inserted extremity

End

No/False

Yes/True
B.3 Propagate waves and display components

Start

Create initial wave; 7. Fill the initial wave

Create new wave; 8. v3d_move_wave (B.5)

If condition

nr_branches > MAX_NR_BRANCHES

Yes/True

display_waves; 9. v3d_vol01_pixmaps

trial_waves || branch_nr < show_progress_counter

No/False

If condition

fraction = nr_branches * 100 / MAX_NR_BRANCHES;

Set all voxels of the trial waves to V3D_VESSEL_VOXEL again

End
B.4 Post processing after the extremity detection

10. v3d_remove_neighbour_extremities ()

Negate all voxels with negative branch numbers

11. Adjust extremities in the boundary layers

12. Adjust extremities in the neck regions

13. !v3d_check_wave_branch_nrs

If condition

Yes/True

nr_branches = -nr_branches;

Propagate wave set free all the waves 14
Clear all seed points 3.1

End

No/False
B.5 The wave propagation

Start

Initial setting

Calculate the distances of each voxel to the wave center

Copy voxel boxes except those of the oldest wave to the new wave

If condition

The neighbor voxel on the boundary

Put neighbor voxels of old wave into new wave

If no new wave

Yes/True

Get extremity 15. v3d_get_extremity

Remove old wave and inset new wave into wave set

Split new wave if disconnected; 16.v3d_split_wave

End
Appendix C

Improved automatic vessel branch labeling

1. Find all seed points in the boundary layers, calculate the PDT

2. Start the wave propagation from the root seed point

While bfound of vessel

3. Label every wave with the branch number and the series number. Adjust the wave direction

4. Adjust and save the center point of each wave as a branch center line

5. Detect and save the bifurcation when the wave is disconnected and initialize the start point using the new wave after disconnection

7. Detect and save the extremities when the wave stops, save the point which is most closest to the center of the last wave

8. Create the skeleton with the extremities and bifurcation points

9. Create the nodes and the vessel graphs

End
Appendix D

The comparison result of down sampling

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<th>Lost/False Extremities</th>
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|               | MAX           | 97%                     |
|               | MIN           | 43%                     |
|               | AVERAGE       | 84%                     |
Appendix E

The comparison result of surface wave propagation

<table>
<thead>
<tr>
<th>Datasets</th>
<th>Surface Lost/False Extremities</th>
<th>E</th>
<th>B</th>
<th>Elapsed time</th>
<th>Improved speed/ratio</th>
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MAX 82%
MIN 24%
AVERAGE 50%
Reference


