THREE-DIMENSIONAL (3D) RECONSTRUCTION OF COMPUTED TOMOGRAPHY (CT) ABDOMINAL IMAGES USING VISUALIZATION TOOLKIT (VTK)

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FACULTY OF ENGINEERING
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[THREE-DIMENSIONAL (3D) RECONSTRUCTION OF COMPUTED TOMOGRAPHY (CT) ABDONMINAL IMAGES USING VISUALIZATION TOOL KIT (VTK)]

ABSTRACT

A computerized tomography (CT) or computerized axial tomography (CAT) scan combines data from several X-rays to produce a detailed image of structures inside the body. CT scans produce 2D of a "slice" or section of the abdomen but the data can also be used to construct 3-dimensional images. However, CT scan unable to accurately represent the internal structure of soft tissues and soft-tissue lesions. Therefore, using the program in Visualization Tool Kit (VTK) is needed to construct a much more clearer 3D image.

To reconstruct 3D images from 2D images of a "slice" or section of abdomen which will be resulting in more accurate CT scanned images that will help medical officer diagnose and plan their treatment more effectively and accurately. A 3D image will be less dependent on human cognitive ability as well as lesser time required for human interpretation, resulting in much easier and more accurate clinical works.

Therefore, in this research, 4 different methods of rendering are employed and compared to determine which method shows the clearest 3D reconstruction images. The rendering methods that are utilized in this research are surface rendering, surface rending with multiplanar rendering, volume rendering and volume rendering with additional features. From the analysis, it shows that volume rendering with additional features has advantage in reconstructing the meticulous tissues and bones of abdomen and helps in providing a detailed data by coordinate, measurement and crop feature in order to determine the exact coordinate for lesions located in abdomen, length measurement of the lesions and crop the outer surface of abdomen to see the inner surface of abdomen, respectively.

However, rendering has it own limitation which it produce artifacts. Therefore, high resolution 2D CT images and high RAM computer are needed to test the algorithm to solve this problem. VTK and C++ is an important tool in development medical 3D visualization software system. In the future, this technology may be the major tool for every hospital to ease the radiologists and medical doctor in diagnosing illness and make plans for the treatment quickly with a low budget.

Keywords: CT images, 3D image reconstruction, VTK, C++, Abdomen

[PEMBINAAN SEMULA TIGA DIMENSI (3D) KOMPUTASI TOMOGRAFI (CT) IMEJ ABDOMEN MENGGUNAKAN ALAT VISUALISASI (VTK)]

ABSTRAK

Imbasan berkomputer tomografi (CT) atau berkomputer paksi tomografi (CAT) menggabungkan data dari beberapa X-ray untuk menghasilkan imej terperinci struktur di dalam badan.Imbasan CT meng hasilkan 2D "kepingan" atau Seksyen abdomen tetapi data juga boleh digunakan untuk membina imej 3-dimensi.Walau bagaimanapun, CT scan tidak dapat dengan tepat mewakili struktur dalaman tisu lembut dan luka-tisu lembut.Oleh itu, menggunakan program dalam Visualization Tool Kit (VTK) diperlukan untuk membina imej 3D yang lebih jelas.

Untuk membina semula imej 3D dari imej 2D "kepingan" atau bahagian abdomen yang akan menyebabkan lebih tepat CT imej yang diimbas yang akan membantu pegawai perubatan mendiagnosis dan merancang rawatan mereka dengan lebih berkesan dan tepat.Imej 3D akan kurang bergantung kepada keupayaan kognitif manusia serta mengurangkan masa yang diperlukan untuk tafsiran manusia, menghasilkan kerja klinikal yang lebih mudah dan lebih tepat.

Oleh itu, dalam kajian ini, 4 kaedah yang berbeza persembahan akan digunakan untuk mengkaji dan dibbezakan bagi menentukan kaedah yang menunjukkan imej pembinaan semula 3D yang paling bersih Antara kaedah yang digunakan adalah persembahan permukaan, permukaan berakhir dengan persembahan multiplanar, persembahan kelantangan dan persembahan kelantangan dengan ciri tambahan. Melalui analisis ini, ia menunjukkan bahawa persembahan kelantangan dengan ciri tambahan mempunyai kelebihan dalam membina semula tisu yang teliti dan tulang perut dan membantu dalam

menyediakan data yang terperinci dengan alat koordinat, alat pengukuran dan potongan gambar untuk menentukan koordinat tempat luka yang terletak di dalam abdomen, pengukuran panjang luka dan membuang permukaan luar abdomen untuk melihat permukaan dalam abdomen .

Walau bagaimanapun, ia mempunyai batasan dalam mempersembahkan ia menghasilkan artifak.Oleh itu, resolusi tinggi gambar 2D CT dan komputer RAM yang tinggi diperlukan untuk menjalankan kaedah ini untuk menyelesaikan masalah ini.VTK dan C++ adalah alat yang penting dalam pembangunan sistem perisian visualisasi 3D perubatan.Pada masa akan datang, teknologi ini boleh menjadi alat yang utama bagi setiap hospital untuk memudahkan para ahli Radiologi dan doktor perubatan dalam diagnosis penyakit dan membuat rancangan untuk rawatan dengan cepat dengan bajet yang rendah.

Kata kunci: imej CT, pembinaan semula imej 3D, VTK, C++, abdomen

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LIST OF SYMBOLS AND ABBREVIATIONS

For examples:

2D	:	2 Dimensional
3D	:	3 Dimensional
CT	:	Computed Tomography
VTK	:	Microsoft Visual Tool Kit
CAT	:	Computerized Axial Tomography
MinIP	:	Minimum Intensity Projection
MPR	:	Multiplanar Reformatting
MIP	:	Maximum Intensity Projection

CHAPTER 1: INTRODUCTION

1.1 Background

Abdomen consist of multiple organs such as liver, intestines and stomach which are vital during food consumption. As they are often encounters foreign object, consume by the host, these organs tend to be easily infected and defunctions especially liver. Operations on these particular organs are also expensive and multiple operations may cost the patient live thus, specialists need to be thorough while planning the surgery.

Organ imaging has proven timelessly as a much clearer depiction for doctors to plan surgery beforehand. Multiple products have been created and developed in order to pursue imaging methods that are able to provide the best imagery of patient's internal. Capabilities to do so not only ensure less follow up operations need to be handled, but also help doctor pre-operation and further check-up post-operation. One of the mostly used technique is CT imaging (Mikla & Mikla, 2014). 3D volume and surface models of the tissue reconstructed using 2D image slices is one of the advancement of medical imaging technology that gives many advantages to medical doctors. For a long time, 3D models have being used in medical applications in many countries, which are used just at some high quality hospitals and medical centers. These equipment are usually expensive and require professionals to operate. It has been an essential tool to assist doctor's diagnosis by information technology, which requires advanced computers with dedicated software.

This research proposes a 3D image reconstruction of multiple 2D CT images of abdomen by using software of Visual C++ 6.0 with Visualization Toolkit (VTK) in order to produce a more accurate CT scanned images. CT scanner as the hardware will provide the images needed and software created will process the given image to produce a clearer and more accurate image. Using this software, a 3D image will be from slices of 2D images captured through a CT scanner. The software will be created using Microsoft

Visual Tool Kit (VTK) with C++ language. C++ language will allow other developers to obtain the coding and alter it to fit their needs as it is a widely used coding language. We believe that using a more general approach can help hospitals and clinics with limited budget to assist patients with better information, help specialist plan operations and treat patients more effectively.

1.2 Problem statement

A computerized tomography (CT) or computerized axial tomography (CAT) scan combines data from several X-rays to produce a detailed image of structures inside the body. CT scans produce 2D of a "slice" or section of the abdomen but the data can also be used to construct 3-dimensional images. However, CT scan unable to accurately represent the internal structure of soft tissues and soft-tissue lesions. Therefore, using the program in VTK is needed to construct a much more clearer 3D images.

1.3 Aim & Objectives

The aim of this study is to develop a program that can visualizes the 2D CT abdominal images into a clear 3D reconstructed 2D CT images in order to have a better pathology view which can help medical officer diagnose and plan their treatment more effectively and accurately with less time of illness interpretation required.

Objectives:

1. To reconstruct 3D images from 2D images of a "slice" or section of abdomen which will be resulting in more accurate CT scanned images.
2. To create a code for 3D reconstruction of CT images by using Visualization Tool Kit (VTK) and C++ software.
3. To determine which rendering is more suitable for 3D reconstruction of CT images in order to produce a more clear CT images.

CHAPTER 2: LITERATURE REVIEW

2.1 Fundamental theory of three-dimensional (3D) reconstruction

2.1.1 3D reconstruction

CT scanner generates 2D images that are separated with equal length gaps according to reconstruction increment. A volume of data is extracted from several 2D images while these gaps are filled by interpolation. Picture elements (pixels) form a 2D picture and a volume is produced from volume elements (voxels). (Figure 1) which can be referred to as points.

2.1.1.1 Interpolation

Unknown values can be estimated by interpolating the known points around it (Lichtenbelt B, 1998). Therefore, this process is important in reconstructing the image of spiral CT and three-dimensional images (Polacin A, 1992). It has been assumed that every location has its own value. The three most commonly used interpolation process are described as below:

1) Nearest Neighbor Interpolation

Interpolated value (IV) is calculated based on the value of nearest point. For each point, it can only be interpolated once.

2) Linear Interpolation

IV is obtained from the linear relationship between two known adjacent points. However, it is unable to calculate for radial-related points as cross-shaped artefacts can occur.

3) Cubic Convolution Interpolation

Calculate IV value based on four or more points. It is a radial operation and is computationally expensive. This method requires a small enough distance between points to validate the presence of IV between the points.

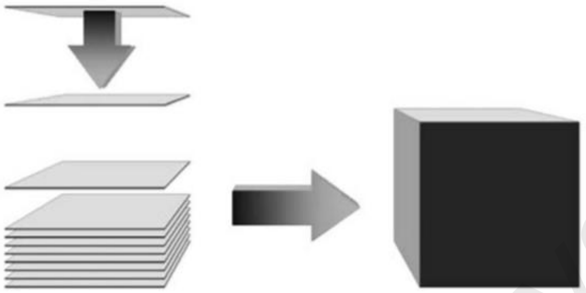

Figure 1 The representation of the images in a virtual 3D space in their respective position produces a cube of data. Images are bidimensional and spaced. The gaps of missing data can be filled through interpolation of the values of the images. In this way, a solid cube of data is obtained. This 3D cube of data is made of elementary units, which are referred as to volume elements (voxels)

2.1.1.2 Representing a volume on a flat screen

The projection of the voxels that form the volume on this surface could represent a volume in 2D picture. Ray casting need to perform the voxels that form the volume may not correspond to the screen's pixels when the volume was projected on a flat screen in order for the projection rays are built from the screen's pixels to the volume (Figure 2) (Lichtenbelt B, 1998). However, these rays may not correspond to the volume's voxels. Therefore, through interpolation, the IV points may be able to form the rays.

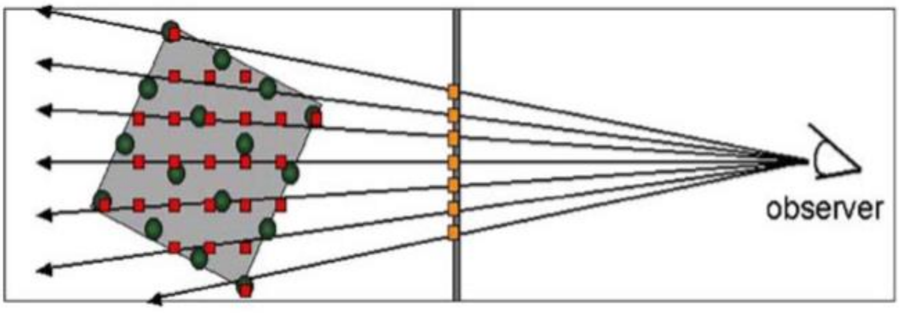

Figure 2 Ray casting. In ray casting, virtual lines are projected from the flat panel to the volume. The value of the pixel of the flat panel is obtained from the values of the points forming the virtual lines. A ray may not intersect the points that represent volume's voxels. The values of the missing points that form the virtual lines are obtained by interpolation from the known samples of the volume. Red squares: interpolated points; yellow square: pixel; green circles: points of the volume (voxels)

2.1.1.3 Assigning a value to the screen pixel

(a) ***Sum***

The sum of the point along the ray value can be calculated from the pixel value of the ray. The resulting image will be somewhat similar to a conventional roentgenogram (Figure 3).

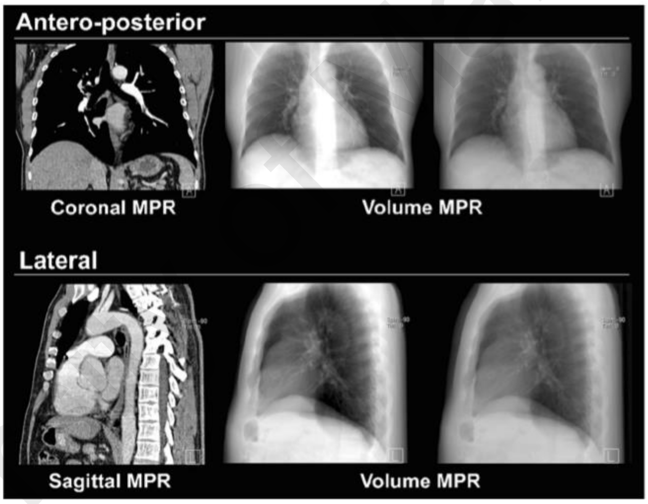

Figure 3 Example that shows how the sum of all voxels in the volume produces the conventional roentgenogram. In antero– posterior (upper panel) and lateral (lower panel) projections, the result of the sum of all the voxels along the observation line is a 2D image, which in principle is comparable to a very thick slab multiplanar reconstruction (volume MPR)

(b) ***Maximum intensity projection (MIP)***

An MIP image in (Figure 4) (Lichtenbelt B, 1998) shows that MIP image's value of pixel is equal to the highest value of interpolated voxel along the ray. In the meantime, Minimum Intensity Projection (MinIP), resulting image of the lowest value of pixel along the ray. The downside of this process is not all voxels are presented in the resulting image. To ensure low percentage of error, axial slices are frequently observed throughout the process. Other than that, as stated by Semba et al. and Sato et al. the lack of depth measuring capability causes hyper-attenuation, producing superimposed two separated hyper-intense structures throughout the rays(Figure 5)(Prokop, Schaefer-Prokop, & Galanski, 1997). therefore, different projection views must be obtained by rotating or trimming the volume. In addition, due to the projective nature of the MIP image, measurements are not reliable since the measurement is dependent on the respective settings.

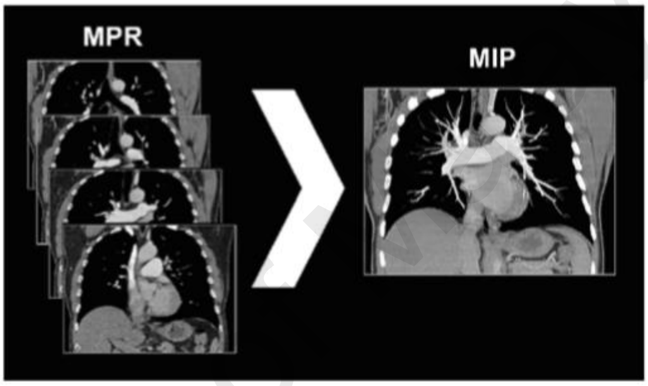

Figure 4 Thick slab MIP. Merging together several contiguous slices (coronal reconstruction on the left side) and projecting the highest attenuation, result in a MIP image (right side)

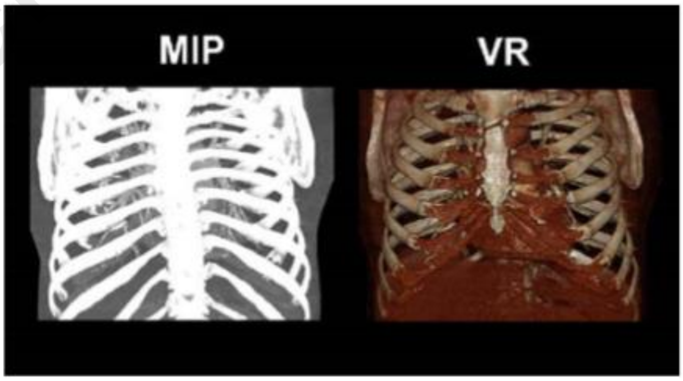

Figure 5 MIP and VR images. In MIP images, hyperintense structures are superimposed and the three-dimensional perception is lost

(c) ***Shaded surface display (SSD)***

This technique represents structure's surface. As shown in (Figure 6), the pixel's value of the final picture corresponds to the value of the point that is closest to the screen and above a selected threshold. The resulting image respects actual anatomy is determined by threshold. However, as stated by (Sato, Shiraga, Nakajima, Tamura, & Kikinis, 1998), SSD image does not provide any densitometric information thus producing confusing result. For example, if the threshold value during stool examination is not calibrated correctly, vascular structures and the contrast material used are represented in the same colour resulting in simulating a presence of tumour as the excrete is visually shown as a part of the mucosa (Rubin, Dake, & Semba, 1995). Therefore, coding that can procure depth using shading scale is needed. The main idea for the coding would be the ability to make voxel in certain area to group up together, projecting a "brighter" layer, creating a depth illusion.

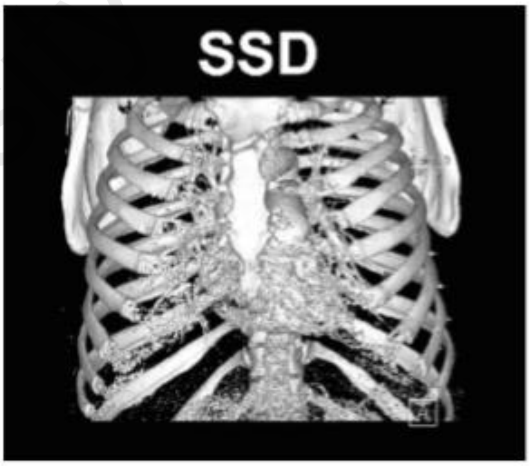

Figure 6 Example of volumetric Surface Shaded Display—SSD

(d) ***Volume rendering and percentage classification***

(Figure 7) each point along the light ray create the pixel on the picture, ranging from 0%- to 100% opacity correlating to the opacity function curve (Udupa, 1999). On a selected interval, the voxels will be presented but, those outside the range will be transparent. The number of opaque voxels will determine the overall pixel values of the image and higher voxels equal to higher opacity in selected intervals.

For CT, visibility of the structures in keeping with their attenuation is defined by shape of the curve as shown in (Figure 7). The pixels are shown through grey- or a colour scale, increasing depth and the densitometric information. As oppose to SSD which its value of pixel depended on virtual distance of final layer to the screen, VR have a better advantage as it can show both spatial and densitometric information.

As for MIP and SSD, visibility and dimensions of structures are strongly affected by opacity function curve and rendering processes, making VR image-based measurement irreliable.

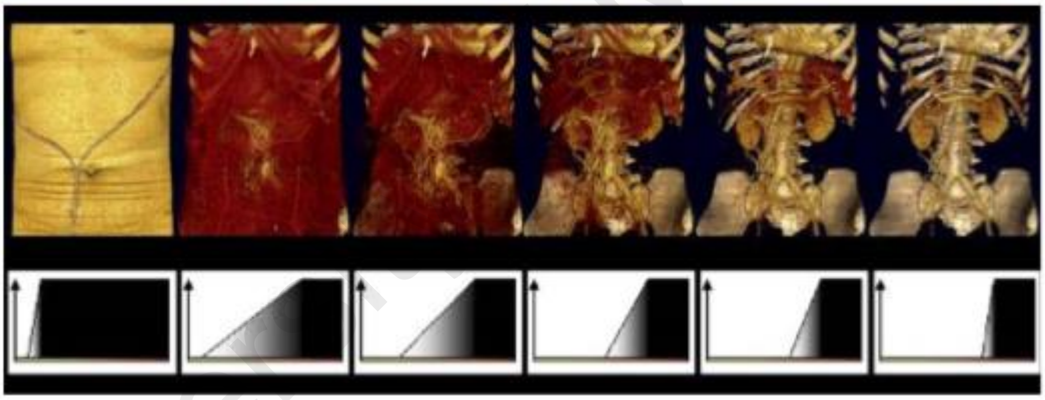

Figure 7 Classification. The shape of the opacity function curve defines the anatomical structures that is visualized according to the attenuation value. From left to right, the soft tissues are progressively made transparent

2.1.1.4 Multiplanar reformatting (MPR)

As the name suggested, multiplanar reformatting (MPR) is created using multiple native layers laid on a different plane (Figure 8) (Lichtenbelt B, 1998). The main usage of MPR is to assess spatial distance between structures projected on each plane. Pixel values that formed in the reformatted plane are interpolated from the closest voxels, making a "thicker" slab of image if more distant voxels are present in the resulting image.

As a result. MPR is prone to less error in measurement due to single plane oriented structures.

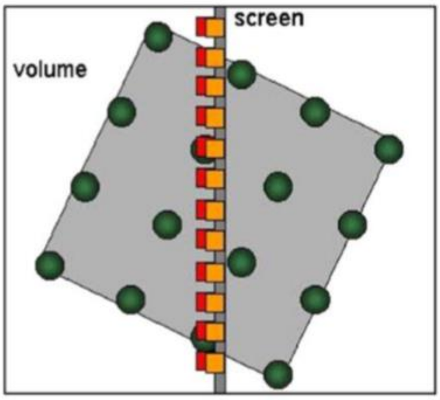

Figure 8 Multiplanar reformation. In multiplanar reformation, the points of the plane crossing the volume are obtained by interpolation from the known points of the volume. Red squares: interpolated points; yellow square: pixel; green circles: points of the volume (voxels)

2.1.1.5 Enhancing the depth perception

Through estimation of the variation gradient of the value of voxels during volume rendering, surfaces can be identified. It is used for applying shades and illumination according to each operation (Lichtenbelt B, 1998; Udupa, 1999). For shading operation, by modifying the light intensity of “color” on the surface pseudo-shading can be created highlighting darker parts of the structures. The effect of illumination from a virtual source of light can be adjusted accordingly to the light’s angle of incidence using illumination operations. A detailed coding for illumination operation can enable the ability to distinguish between a smooth surface and rough surface by creating a different reflection for both smooth and rough surfaces (Figure 9).

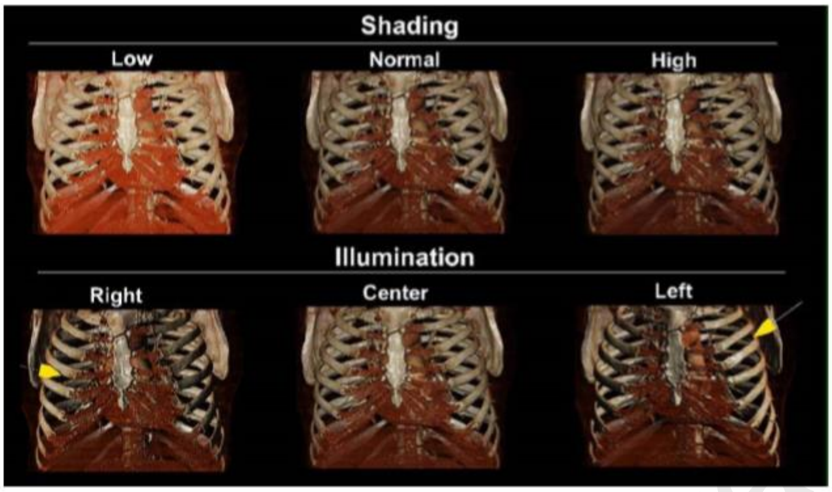

Figure 9 Shading and illumination. Shading modify the colour of the phantom according to the virtual distance from the observer, to the texture and the features of the surface. Illumination modify the colour of the phantom according to the direction and the features of the virtual source of light. Shadows are generated accordingly. The respective effect of different shading levels (upper panel) and illumination orientations (lower panel) are displayed

2.1.1.6 Segmentation

Segmentation is used for labelling purposes on voxels that form structures within a volume. By differentiating density and homogeneity, the overall basis of morphology, the location of an object within the volume and its inherent structures can be identified (Höhne & Hanson, 1992). Without useful identification, segmentation cannot be performed accurately, especially when structures or objects with similar density surround or connected to the target object.The advantages in segmenting is the capability to accurately assess volume, surface and histogram analysis on segmented object (Figure 10) (Frericks et al., 2004). Moreover, segmentation is important in screening programs that are used for automated lesion detection and to unwrap hollow viscera (Summers et al., 2000).

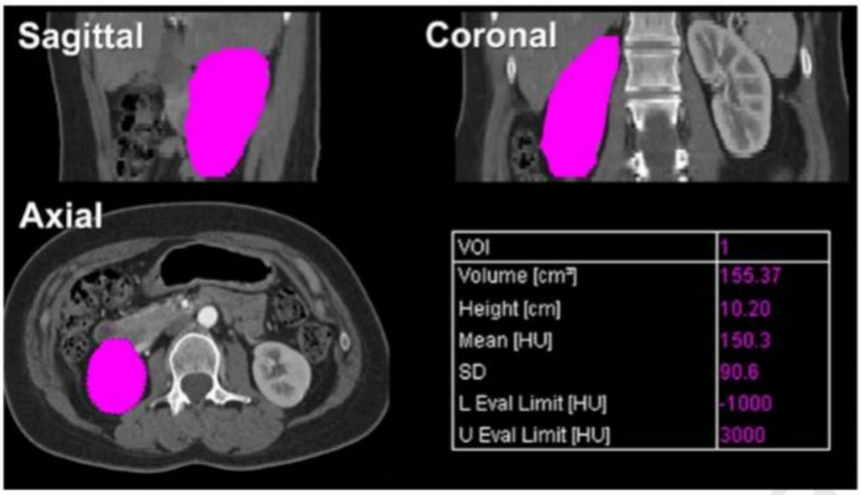

Figure 10 Segmentation. The use of segmentation tools allows measurement of the exact volume of organs and calculation of the mean attenuation such as, in this case, with a right kidney

2.2 Clincial Applications in 3D Reconstruction of Abdomen CT Images

The main disadvantage of transverse CT based classical radiologic was its inability to depict most conditions (Cody). 3D images are helpful in most cases as they can reflect said conditions in resulting images.

2.2.1 Liver

2.2.1.1 Liver Transplantation

The only method to avoid death due to liver failure is liver transplantation and it is considered as the primary treatment for liver-related incidents. Producing a more accurate imagery on pre and post-operative condition of said organ, particularly in hepatic artery, portal and hepatic veins region is essential to ensure safe hepatic transplantation. Using 3D reconstruction methods, images can be produced more clearly and accurately depicting the current state of the hepatic region shown in (Figure 11) (Kamel IR, 2001).

To evaluate living related transplant donors, there are several conditions are needed:

1) The liver parenchyma is where assessment for focal liver lesions, and fatty infiltration take place to ensure no immunities that can contraindicate transplantation and cause negative reaction in the receiver’s body.

2) During surgical planning, hepatic and arterial venous anatomy needs to be marked and mapped correctly to easily identify important vascular. This can avoid further unnecessary surgery(Kamel IR, 2001).

3D reconstruction is important to provide information on any anomaly on a vascular region, ensuring a normal vascular supply. This in return reduces the risk for rejection by the receiver’s body and ensures smooth transplantation operation. 3D CT graphics can help professionals to easily identify major variations of the hepatic vein confluences, hepatic arterial variants and portal vein trifurcations. 3D reconstruction can effectively differentiate portal and hepatic venous anatomy clearly and easily identify the hepatic artery and its branches especially when compared to a conventional angiography. As a result, the overall cost of diagnosis will be lower and patients are prone to less risk. The downside of this method is its inability to depict anomalous biliary anatomy which can cause several repercussions such as graft failure and post-surgery bile to leak. The method that is currently being used to differentiate binary anatomy is intraoperative cholangiography. (Kamel IR, 2001).

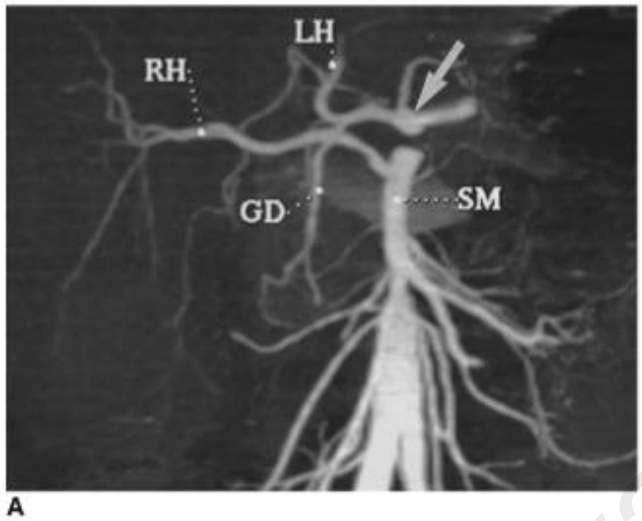

Figure 11 Liver donor evaluation in a 50-year-old man with CT angiography. Maximum intensity projection image (A) demonstrates hepatic arterial anatomy with left hepatic (LH) artery originating from celiac trunk (arrow) and right hepatic (RH) artery arising from celiac trunk (arrow) and right hepatic (RH) artery arising from superior mesenteric (SM) artery. 3D surface rendering in the same patient depicts entire hepatic lobe volume

2.2.1.2 Hepatic Resection

By estimating liver volume and virtual hepatectomy with 3D images pre-surgery, the planning of hepatic resection will be more fruitful (Maher et al., 2004). Advantages when using 3D imagery techniques to estimate liver volume, especially when combined with clinical and laboratory evaluation, includes the capability to predict post-surgery liver failure, enhance volume of embolization procedures and help during surgery planning for bilobatic patients. As a result, the needs for conventional angiography decreases, reducing overall cost and risk to patients.

2.2.2 Urinary Tract

Urologists believe that the application of 3D reconstruction in CT urography allows doctors to view images of the urinary tract in the coronal plane, similar to excretory urography images (Caoili et al., 2002). Through evaluation on excretory urography images, radiologists are more capable to characterize certain pathologies including those locales to renal calyces and papillae (Figure 12). 3D reconstruction is useful for diagnosing patients with anatomic variation of the urinary tract, locating present ureteric obstruction and detecting contour abnormality on renal outline (Figure 13) (Figure 13) (Schreyer, Uggowitzer, & Ruppert-Kohlmayr, 2002). In order to achieve maximum efficiency, 3D reconstruction images need to be viewed accompanied by transverse images. Some abnormalities on the urethral and bladder wall may not be visible in 3D imagery alone.

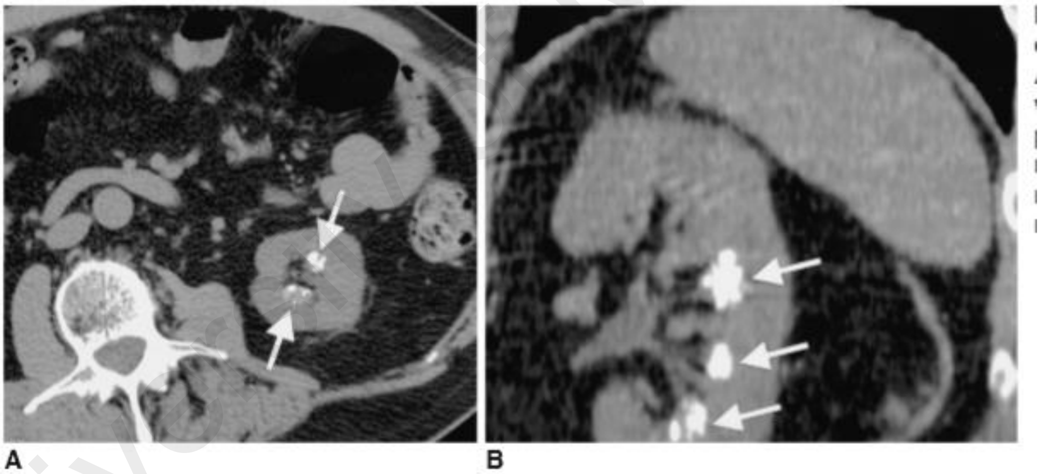

Figure 12 Coronal reformats aid with characterization of caliceal abnormalities. Axial CT image (A) of a 31-year-old woman shows calcification in the renal papillae (arrows). Coronal multiplanar reconstruction (B) shows typical radiographic features of medullary nephrocalcinosis (arrows)

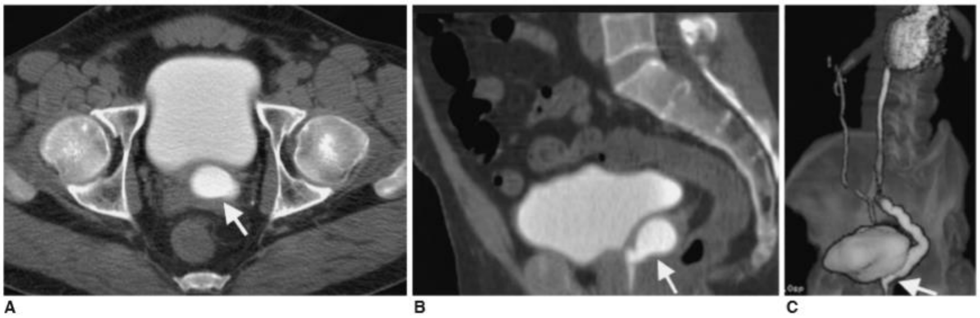

Figure 13 3D CT can combine advantages of intravenous urography and voiding cystourethrogram and retrograde urethrogrogram. Axial CT image (A) in 47-year-old man with recurrent urinary tract infection shows a dilated, ectopic left ureter (arrow) within the prostate. Sagittal multiplanar reconstruction (B) shows a dilated, ectopic ureter (arrow) opening into the posterior urethra. 3D surface rendering (C) demonstrates anatomic relationship of the ectopic ureter to the regional anatomy

2.2.3 Gastrointestinal Tract

3D CT reconstruction images can help to identify precise location of stomach, small bowel and colonic lesions (Figure 14).

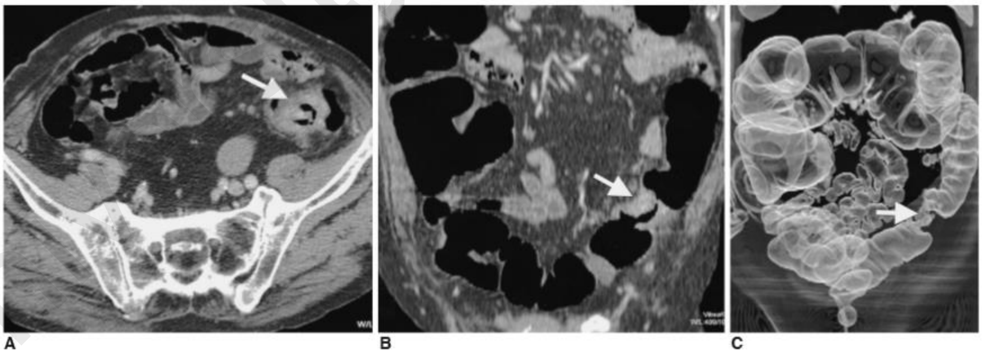

Figure 14 3D CT of malignant colonic stricture in a 73-year-old man. Axial CT (A) and coronal multiplanar reconstruction (B) images show circumferential short segment thickening of the sigmoid colon (arrow) suggestive of colon cancer. 3D CT colonography (C) as a "double contrast barium enema" simulating image, reveals short segment "apple-core" lesion (arrow) in the sigmoid colon

2.2.3.1 Colonic Stricture

By reconstructing the area of narrowing with 3D CT imagery, it is possible to accurately determine the location and condition of a colonic stricture. By viewing the structure in multiple planes, details on the malignant stricture can be thoroughly confirmed and characterized into single and double contrast barium enema. Other benefits include locating any injury on the mucosal area, 'determined length of the stricture and confirming the presence of intussusception (Figure 15).

Figure 15 Axial image (A) shows a fat containing intraluminal mass (arrows) in a loop of ileum in a 49-year-old woman with intussuscepted Meckel's diverticulum. Coronal multiplanar reconstruction image (B) shows a tubular fat containing filling defect (arrows) in a loop of ileum in a 49-year-old woman with intussuscepted Meckel's diverticulum. Coronal multiplanar reconstruction image (B) shows a tubular fat containing filling defect (arrows) in the ileal lumen that was contiguous with the mesenteric fat

2.2.3.2 Bowel Ischemia

3D rendering technologies and dual phase acquisition CT scan when combined creates a superior mesenteric artery (SMA) and superior mesenteric vein (SMV) angiogram that can detect any stenosis or thrombosis in the bowel area (Horton & Fishman, 2002). By further enhancing bowel area, it is possible to accurately determine any acute or chronic bowel ischemia.

2.3 3D Rendering Technique in Medical Imaging

MPR, surface rendering (SR) and volume rendering (VR) are the three broad classes of 3D imagery techniques.

2.3.1 Multiplanar Rendering

Multi planar reformatting (MPR) is a two-dimensional reconstruction imagery technique that forms CT images on multiple planes and using volumetric data can visualize resampled grey values at arbitrary cross section. (Kumar & Vijai, 2012).This techniques enable to view an entire structure from multiple angles for instance, an axial slice is cut into a sagittal or coronal plane, enabling side view and top view as opposed to only linear view of the structure. Relationship between organs can be easily viewed, easing the planning process pre-surgery. MPR technique allows for specialists to view from different angles and is not limited to viewing from the direction the organ was scanned. Using MPR technique, 3D images can be reconstructed faster allowing easier diagnosis and pre-surgery planning during emergency. The main drawback of this method is the visualized data lacks depth as it is only a 2D image reconstructed into a 3D image.

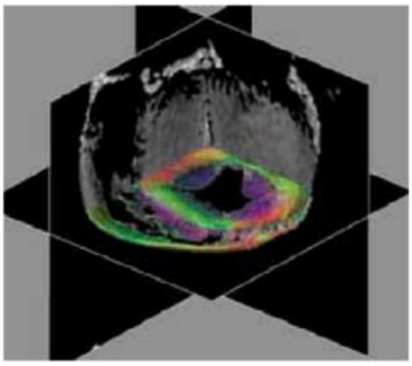

Figure 16 Multiplanar Rendering

2.3.2 Surface Rendering

Surface rendering is a 3D imagery technique that visualizes structure based on a data set of basic elements which represent either the whole structure or boundary that shape the structure. An iso-surface is a surface that is made of point at a constant value and is a 3D analog of iso-contour. Using data volume, two most popular methods to create iso-surface are contour based surface reconstruction and iso-surface extraction algorithm.

2.3.2.1 Contour based surface reconstruction

CSBR is an iso-surface construction method that creates iso-surface from extracted iso-contours over a set of cross-sectional contours (Fuchs H. , 1977). In case of producing 3D structure, a simple manual method is employed where images are resized to fit table-top observation and are stacked in sequence of CT scan images and equally sized transparent spacers. This combination then formed an in-line semi-transparent stack with approximate size to real-world counterpart with multiple angle viewing.

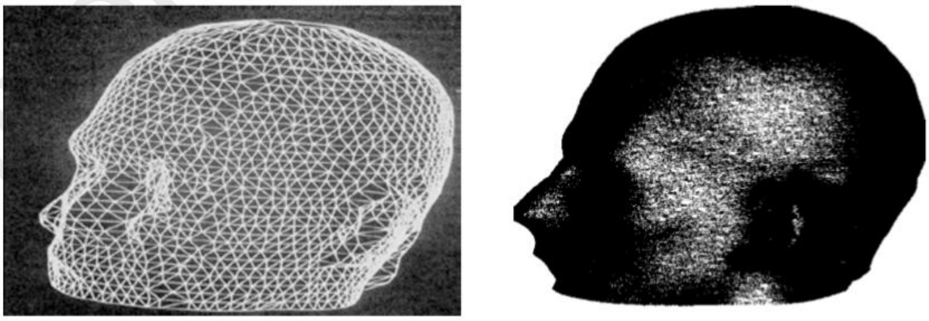

Figure 17 (left) Optimal tiled surface defined over the contours; (right) 3D reconstruction of face

2.3.2.2 Isosurface Extraction based on Marching Cube

Marching Cube is one of the algorithms used in iso-surface extraction. The three main steps contained in this algorithm is locating the surface based on user specified values, creating triangles and optimizing the image quality by replotting every vertex of triangle tiles into normal to the surface (Lorensen & Cline, 1987)

For locating the surface points, a median is created where assigned vertice's points need to be above or equal to the median value and can be considered as inside vertices. Points with lower than median value are considered as outside vertices. The next step is using surfaces from 3D medical data, triangle models are created with constant density. The whole process of 3D image reconstruction can be broken down into multiple categories based on their function. Segmentation modules provide relevant information of each participating slice. Obtained output is then used in the algorithm to produce iso-surfaces. Finally, to enhance searching of images, only voxels inside vertices(iso-surface) are made available for searching. However, basic iso- surface method using MC algorithm has many drawbacks including producing a large amount of triangle meshes, high number of iso-surface patches and wrong surface location to name a few.

A workaround was suggested back in 2008 to overcome large production of triangle meshes by utilizing filter module, segmentation module and mesh optimization modules(Jun, Miao, & Ningyu, 2008). To decrease the surface's location searching time based on input data, filter and segmentation module is used. These modules changed the single loop traversing method into small quantities traversing method allowing faster calculation and searching time. Mesh optimization modules merged triangle meshes to ease the rendering process.

2.3.3 Volume Rendering

Volume rendering applied the method of backward mapping, where each pixel on the view plane fires a ray intersecting with any voxels on its way, collecting their information and location in the process. This technique is more advanced compared to the MC algorithm in the sense that they are able to take into account transparent objects and project the structure as such. Using ray casting (backward mapping), VR is able to project structure in its natural form and take into account the state of the structure rather than project each structure as solid.

Another reason that differs volume rendering to surface rendering is the way it interprets data value. As opposed to surface rendering which creates outlines based on the data sets of basic elements, volume rendering takes into account the opacity of each voxel. The method implies that all voxels in the region are semi transparent and proceed to give opacity values to each voxel. The transfer function containing data on the base image is used to input opacity value onto each voxel and determine transparency on the resulting image. The modeling basically proposes both the interior of a material and the boundary between materials to be colored(Drebin, Carpenter, & Hanrahan, 1988). In the simplest form, ray casting can be described as the intensity of light that is projected into our eye and how the brain translates the object into opaque, transparent and translucent images.

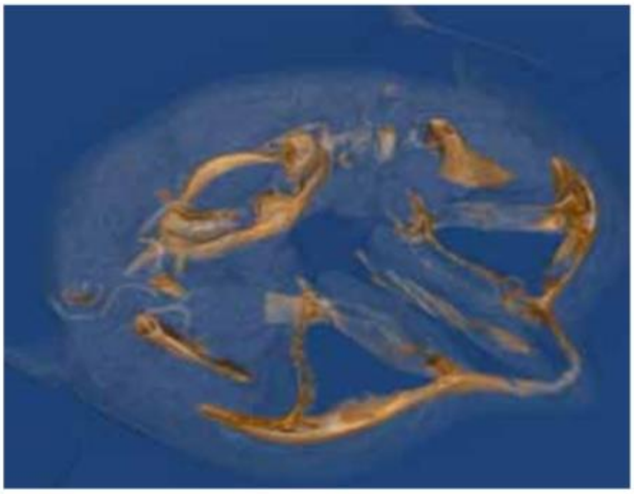

Figure 18 A CT dataset visualized by volume rendering

The several useful features that can be obtained while using volume rendering include the ability to visualize structure from any direction by adjusting the incoming ray, being able to adjust opacity value to view structure in its natural form of transparency and finally enhance interpretation of 3D models by applying color and shades.

2.4 Visualization Tool Kit (VTK) in Three-dimensional (3D) Image Reconstruction

VTK is developed by the United States Kitware is an open source, object oriented software system for computer graphics, visualization, and image processing, and visualization with provided features that was summarized in (Table 1) used by thousands of researchers and developers around the world. It supports a wide variety of visualization algorithms and advanced modeling techniques, and it takes advantage of both threaded and distributed memory parallel processing for speed and scalability, respectively. VTK consists of a C++ class library, and several interpreted interface layers including Tcl/Tk, Java, and Python. In addition, dozens of imaging algorithms have been directly integrated to allow the user to mix 2D imaging or 3D graphics algorithms and data. The design and implementation of the library has been strongly influenced by object-oriented principles

(Hanák I., 2003). It usually has important limitations such as low efficient code execution, poor computing capacity (Tamura Y., 2016).

In fact, VTK is an open source class library rather than a single system, it encapsulates numerous and frequently-used graphical operation and image processing algorithms in different classes, these classes are easy to be understood and called. The object libraries can be embedded into applications; we can also develop the library functions of ourselves on the base of VTK's basic functions. At the same time VTK has excellent streaming and cach, processing three-dimensional data produces a high memory demanding, once the program fails to request memory to the operating system, the program will make mistakes, sometimes the failure even leads to program crash, the efficient streaming and cach can solve the problem better, in addition, VTK also supports multithreading processing and has high execution efficiency. Compared with MATLAB and OpenGL library, VTK has the advantages of flexible application, better reconstruction quality and higher reconstruction speed; it can also accomplish manipulation such as image shrinking, rotating, shifting and feature extraction. The initial aim of developing VTK is the application in the medical field, VTK contains many advanced modelings and a series of visualization algorithms such as the MC Algorithm, The Ray-Casting Algorithm and so on. Since the appearance, VTK has been widely valued, d, used and improved continually, now it has become the most famous software development kit in the image visualization field.

VTK consists of two subsystems, one is the C++ Class Library written in C++, the other one is the interpretive layer and the layer is constructed according to certain rules, it supports script languages. The structure not only can generate effective algorithms with C++ but also keeps the characteristic of script languages at the same time, which means the users can choose their familiar languages and these languages all have their own GUI development support.

VTK adopts the pipeline architecture and sets two types of rendering processes (surface rendering and volume rendering) in the architecture of the data pipeline; the two processes adopt different visualization algorithms. The most salient characteristic of VTK programs is the pipeline, it means that a VTK program is a complete render pipeline, the forepart of the pipeline is the Visualization Model Pipeline which consists of data source, reader, filter and so on, it is used for obtaining image and preprocessing (image segmentation, smoothing and sharpening) source data information and then transforming the information into graphic data. The posterior part is the Graphic Model Pipeline, which consists of actor, camera, ray, property, mapper, renderer, render window and so on; it is used for transforming the graphic data into image. In other words, the visualization process establishes the geometric expression and then the graphic process processes it. The render pipeline can accomplish three-dimensional reconstruction of point, line and surface (Bruggmann, 2016).

As VTK is an open source and free software with powerful 3D graphics processing function, an excellent architecture, high flexibility, outstanding portability and expandability, recently it is widely used in image processing, computer graphics and visualization in scientific computing; meanwhile, it has become a good choice for development of medical image visualization. Therefore, this software is the most suitable tool for reconstructing 3D image from a set of CT images using VTK and Visual C++ 6.0 because of its open source toolkit professionally designed for computer graphics purposes (Figure 19).

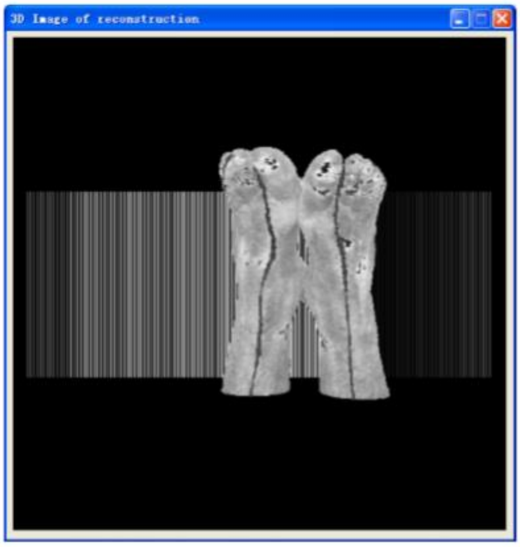

Figure 19 3D foot reconstruction

Table 1 Features available in Visualization Tool Kit (VTK) software

Features	**Description**
Filters	Filter enables VTK applications to manipulate data using its function to receive and provide derived data. Combined filters create dataflow networks, producing a visually comprehensible image.
Graphics System	Graphic system (OpenGL in most cases) enables rendering of abstraction layers, compiling visuals into a single image.
Data Model	Data models is a set of data that mirror real world physical science, allowing solutions created to be true to real life.
Data Interaction	In VTK, data interaction tools enable users to understand the context of data obtained and add a more user-friendly interface to programs.

2D Plots and Charts	2D plots and charts enable users to operate data sets to and from using Python coding. It also allows users to interactively manage and understand obtained data.
Parallel Processing	Parallel processing enables scaling of distributed memory to be parallel process under MPI.

CHAPTER 3: METHODOLOGY

3.1 VTK Programming

In this experiment, all of the slices of images need to be read as a volume into the system by using the function vtkJPEGReader in VTK. As the data input become volume, marching cubes algorithm can be applied for reconstruction of 3D image. In this paper, 4 methods were approached to find a clear 3D reconstruction of 2D abdominal images which are surface rendering, surface with multiplanar rendering, volume rendering and volume rendering with additional feature.

3.1.1 Method 1: Surface rendering

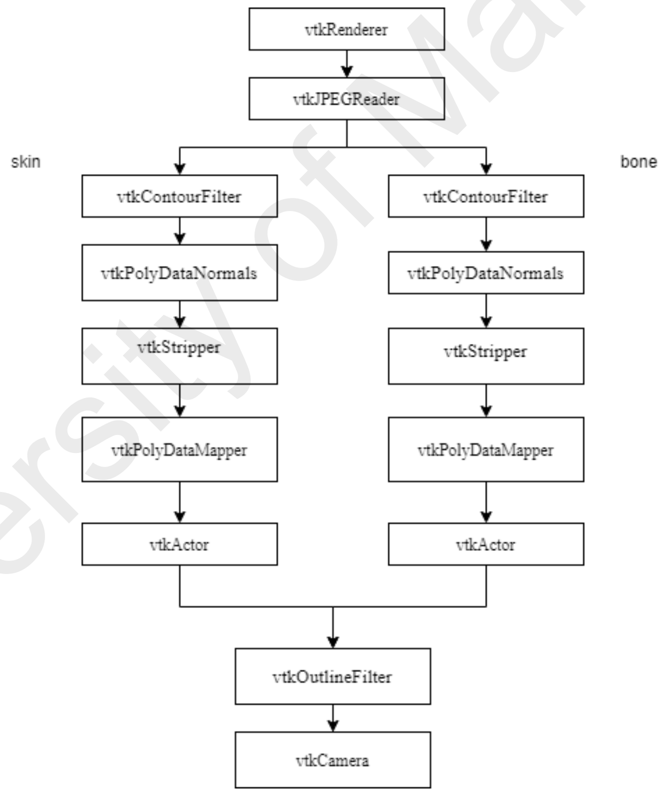

Figure 20 Pipeline for surface rendering method

vtkRenderer was functioned to create the renderer , its window, and the interactor. The renderer was drawn into the render window, mouse- and keyboard-based interaction was enabled with the data within the render window. Next, the vtkJPEGreader is functioned to compose the volume by reading a series of 2D image slices. The slice dimensions are set in which 400 slices were used, and the pixel spacing which is 512x 512 defines the dimensions of a slice of 2D CT images. The filenames with the 2D CT images slices using the format FilePrefix were constructed.

The extracted two isosurfaces that represent the bone and skin structures were read by using the volume dataset, and then displayed. The ideal contour value of human skin is 500 and 1150 for human bone. However, it can be used for this experimets since it requires high RAM PC to run it therefore the value was set low as for the skin contour value we used 100 meanwhile for the bone contour value we use 200. Once generated, a vtkPolyDataNormals filter was used after the volume dataset was read in order to create smooth surface shading during rendering. The greater the vykPolyDataNormals filter, the shared edge will be considered as "sharp". The vtkStripper was used to create triangle strips from the isosurface, this will result in fast rendering. vtkOutlineFilter was created to draw an outline providing context around the data and by using RGB color range code, 0.0 were used to create a black outline.

An initial camera view is created by using vtkCamera.This was used in order to position the camera to look at the data in this direction. The Dolly() method was used to move the camera towards the FocalPoint in order to enlarge the image to zoom in. Then, the background color is set within the range of RGB color codes which are 0.0 (black)~1.0 (white). At the same time, the renderer size is created by using the pixel size which is 512 x 512.

3.1.2 Method 2: Surface rendering and multi planar rendering

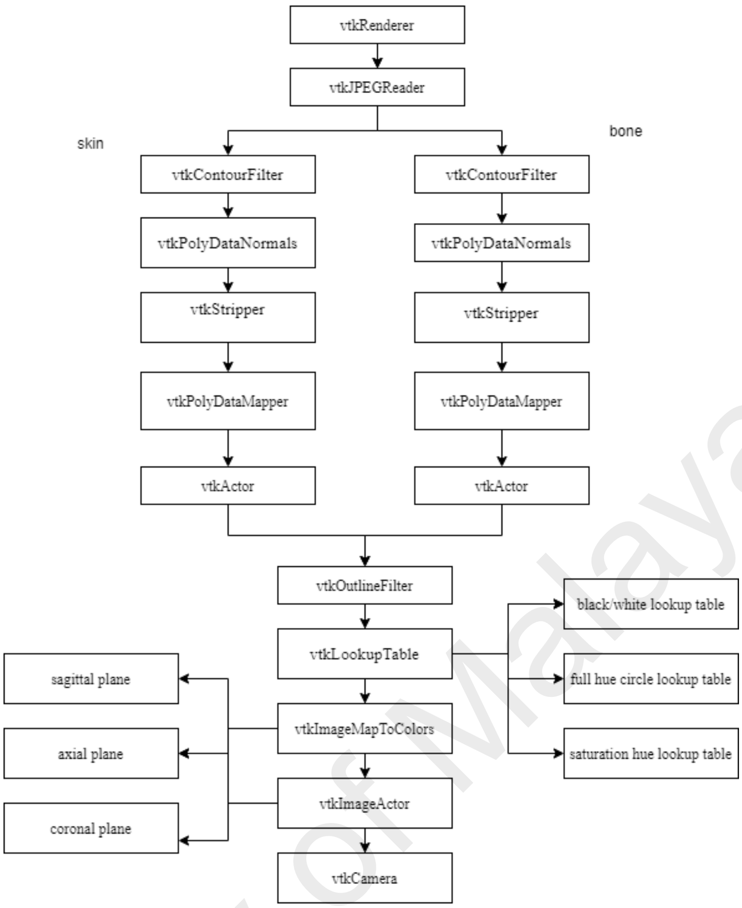

Figure 21 Surface rendering and multi multiplanar rendering method

This method has the same pipeline with Method 1 (Surface rendering) which used a surface rendering method starting from vtkRenderer until vtkOutlineFilter that was shown in Figure 20. Next step is three orthogonal planes passing through the volume were created by using a multiplanar rendering method. In order to have a different coloration, each plane used a different texture map. In this method the maximum SetTableRange was 2000 in order to have a huge table scale.This method was then started by creating a black/white lookup table (bwLut) using vtkLookupTable. Next, a lookup table that consists of the full hue circle (hueLut) is also created using vtkLookupTable. Finally, a lookup table was created with a single hue but having a range in the saturation of the hue (satLut).

Each of these lookup tables used HSV color space that were defined as Hue, Saturation, and Value. Before this, RGB (red, green, and blue) were used to describe the colors, but in this method HSV was used because it describes colors similarly to how the human eye tends to perceive color by using color, vibrancy and brightness meanwhile RGB only can define the primary color only. In HSV, Hue represents the color type, it describes the color of the angle on the above circle, and it can be ranged from 0 to 255, with 0 being red. Meanwhile, the saturation describes the vibrancy of color which it has range from 0 to 255. The decrease in saturation, the more gray is present in this color and becomes more faded. Therefore, in this method we just use 0.0 to 1.0 range only. Lastly, the value represents the brightness of color which ranges from 0 to 255 which 0 is completely dark.

The first plane which is a sagittal plane that is used to divide left and right parts of abdomen was created out of three planes. The vtkImageMapToColors filter maps the data by using the corresponding lookup table created above. The vtkImageActor is used to display images on a single quadrilateral plane and it is a type of vtkProp which functions to abstract the volumes dataset . The pipeline will only use the data that were input in DisplayExtent and the vtkImageMapToColors will only process a slice of data stated. Therefore, in this experiment, the extent range was used between 0-400 which represents the number of 2D slices images that were used as an input volume. Meanwhile for the second plane which is the axial plane which divides head and tail parts of abdomen (cranial and caudal) and third plane is the coronal plane that divides front and back of abdominal parts (posterior and anterior) have the same approach same as sagittal plane before except that the extent differs which can be summarized in Figure 21 above.

3.1.3 Method 3: Volume rendering

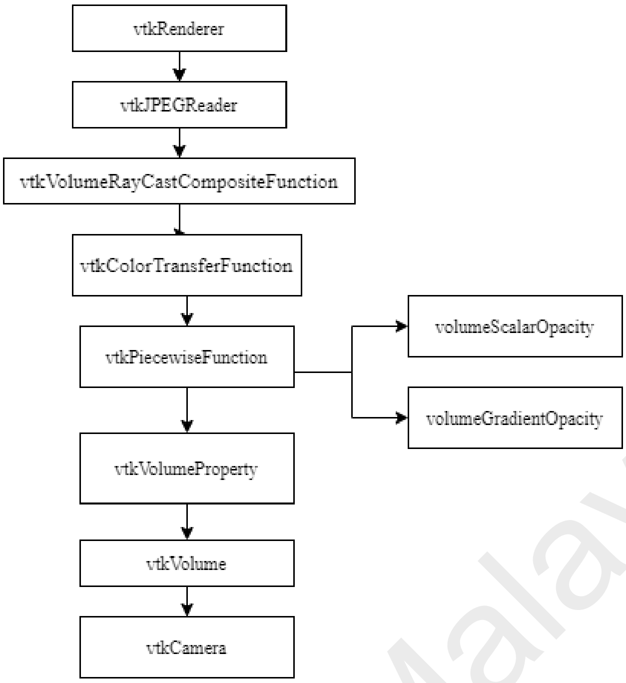

Figure 22 Pipeline for volume rendering method

The vtkJPEGreader was used to read a series of 2D slices images that compose the volume and it will be displayed by ray-cast alpha compositing. vtkRayCastCompositeFunction is used to composite the ray cast along the ray meanwhile vtkRayCastMapper that was composed after the vtkRayCastCompositeFunction is needed to map the ray-casting.

vtkColorTransferFunction maps voxel intensities to colors. It is modality-specific, and often anatomy-specific as well. The goal is to one color for flesh is between 500 and 1000 and another color for bone 1150 and over.

The vtkPiecewiseFunction was divided into 2 functions which are the volumeScalarOpacity and volumeGradientOpacity. volumeScalarOpacity was used to control the opacity of different tissue types by using the scalar of the volume range from 0.0~1.0 which 0.0 is transparent meanwhile 1.0 is completely opaque. The volumeGradientOpacity function was used to decrease the opacity in the "flat" regions of the volume while maintaining the opacity at the boundaries between tissue types. It also ranges between 0.0~1.0. The gradient is measured as the amount by which the intensity changes over unit distance. For most medical data, the unit distance is 1mm.

The vtkVolumeProperty were divided into two functions which are color and opacity functions to the volume, and sets other volume properties. In order to have high-quality rendering, the linear of interpolation is important. In this function, the ShadeOn option enhances the volume appearance to make it look more "3D" by turning on directional lighting. The main drawback is that the quality of the shading depends on the gradient of the volume. However it is hard to determine the accurate calculation and the noisy data cause the decrease of gradient estimation. Therefore, this problem can be solved by decreasing the Ambient coefficient while decreasing the Diffuse and Specular coefficient in order to decrease the impact of shading. In this experiment low ambient coefficients were used which are 0.2 and Diffuse and Specular 0.6 and 0.4 were used respectively in order to decrease the shading impact. The Ambient will be decreased and the Diffuse and Specular will be increased in order to have a high impact of shading.

Lastly, the vtkVolume which acts as vtkProp3D to control the position and orientation of the volume in world coordinates. Finally, the volume was set to the renderer.

3.1.4 Method 4: Volume rendering with additional feature

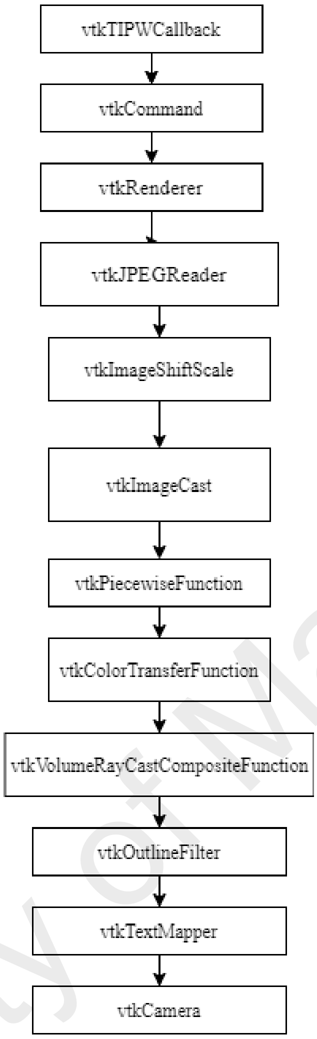

Figure 23 Pipeline for volume rendering with measurement feature

In this method, it used the same rendering as Method 3 (Volume Rendering) with 3 additional features which are crop feature to crop outer surface in order to see the inner surface of abdomen, length measurement feature to measure the length of interest point in abdomen & coordination feature to identify coordinates of certain points that the user would like to look in detail.. This method can be summarized in Figure 23 above.

A callback function is created first since it serves as the "observer" in the "command/observer" design pattern. This function was used to send out a command by notifying all observers of the event in VTK. The vtkCommand was used then to imply the function. This in turn causes the pipeline to update and clip the object and callback for the interaction. In this function, crop, coordinates and length measurement features were coded.

The vtkJPEGreader was used to read a series of 2D image slices that compose the volume which have the same method as all the methods above. Next, pixels are shifted and then scaled by using vtkImageShiftScale, pixels are shifted and then scaled. The value was set into the pixel. This function was used to set the output scalar type similar to vtkImageCast. This is because shift scale operations often convert data types. Therefore, vtkImageCast filter was used to cast the input type in order to match the output type in the image processing pipeline. VtkPiecewise was created to have a piecewise function mapping. This function mapping allows to add extra control points and allows the user to control the function between the control points.

vtkColorTransferFunction use a color mapping in RGB (red, green, blue) that uses piecewise hermite functions to allow interpolation. Next, vtkVolumeRayCastCompositeFunction was used to have a ray function that can be used within a vtkVolumeRayCastMapper. This function performs compositing along the ray according to the properties stored in the vtkVolumeProperty for the volume. Next the vtkVolumeProperty was used as same as Method 3 above to set the volume properties. However, in the vtkVolumeProperty an additional property was added which is specular power to intensify and sharpen the edges if the area where the specular light is present which may range from 0~∞. The higher the specular power, the higher the light will present.

Next, vtkOutlineFilter was used to create outline of the data context. In this filter, 2 spheres were created for the coordinates feature and length measurement feature. Lastly a cell picker was created. A vtkTextMapper and actor was created to display the results of picking. In this cell picker, vtkImplicitPlaneWidget was used to create a finite plane with four handles which can be used to resize the plane, a normal vector to rotate the plane, and the plane itself to be picked and translated.

CHAPTER 4: RESULTS

4.1 Surface Rendering Result

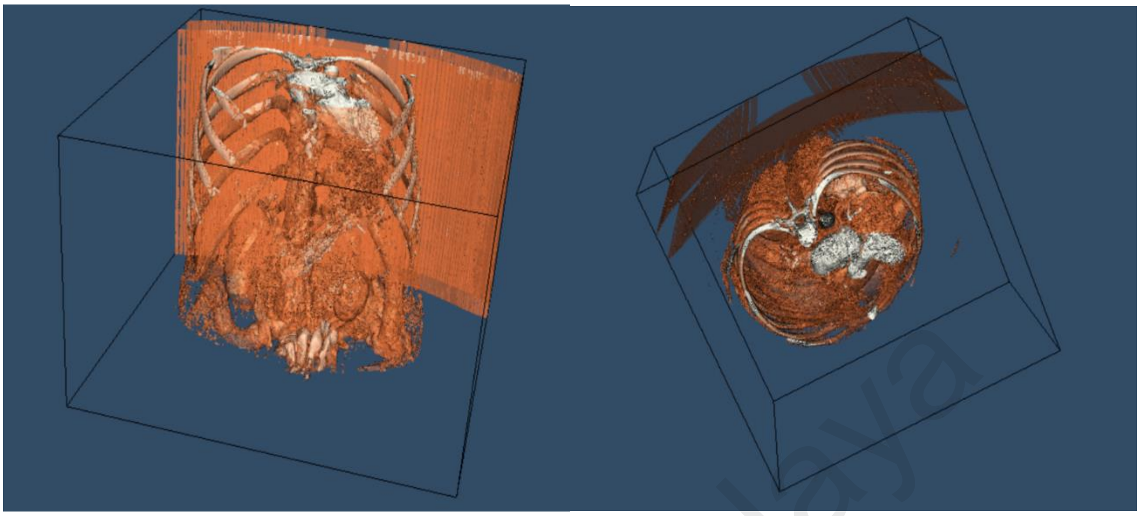

Figure 24 Method 1 (Surface rendering) results (Left) front view, (Right) top view

Surface rendering (Method 1) result shows gross 3-D relationships most effectively as seen in the rib cage in (Figure 24). It realistically shows organs in supposed locations and their current state However, it suffers in crowded areas with lots of artifacts and cannot effectively display structures hidden behind an overlying bone or located beneath the bone cortex..

4.2 Multiplanar Rendering Result

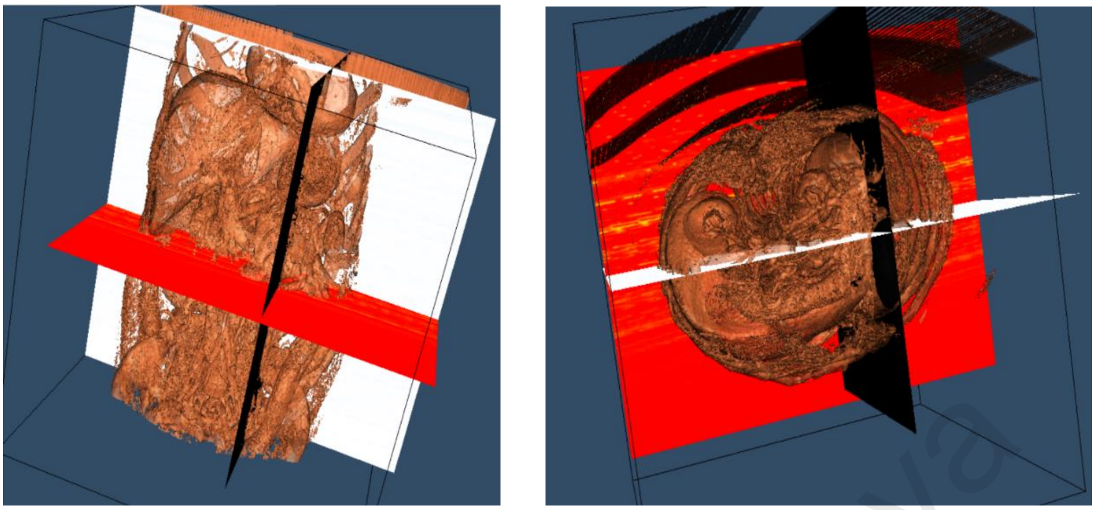

Figure 25 Figure 28 Method 2 (Surface and multiplanar rendering) results (Left) front view, (Right) top view

Meanwhile, in Multiplanar rendering (Method 2), the axial slices are cut into the sagittal or coronal plane allowing to view the entire structure from the side or from front to back rather than as an axial slice cut across the structure (Figure 25) enabling to be viewed from multiple angle. The main drawback of this technique is that it is not a 3D image, making it much inferior compared to Method 3 and Method 4 as it is more of a static picture rather than a "flexible" reconstruction of an image with colors and shades.

4.3 Volume rendering result

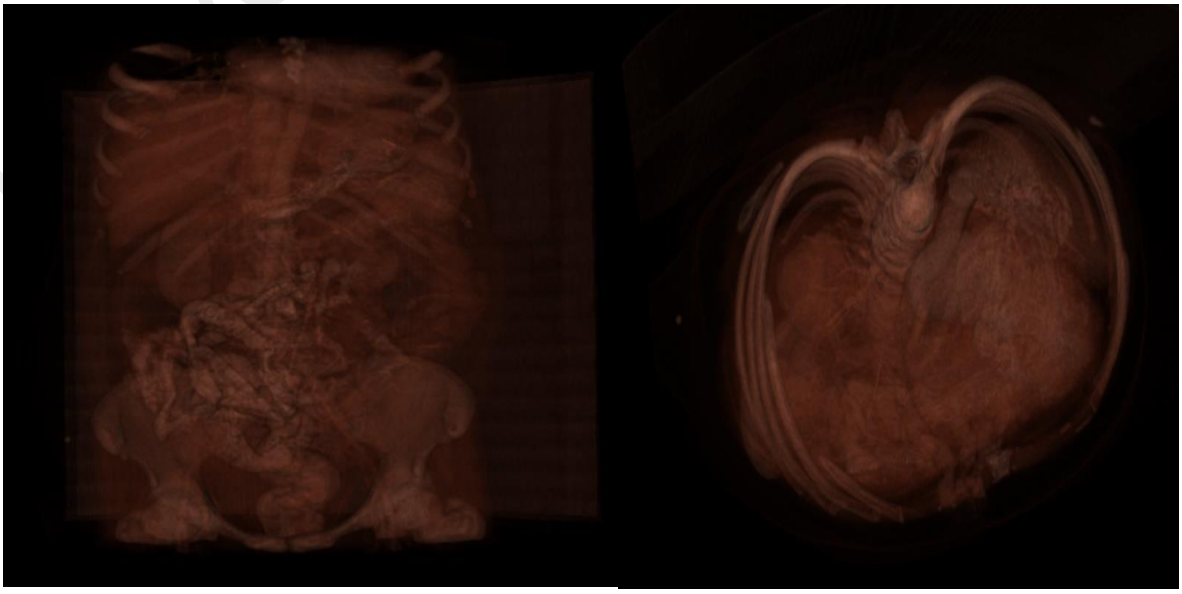

Figure 26 Method 3 (Volume rendering) results (Left) front view, (Right) top view

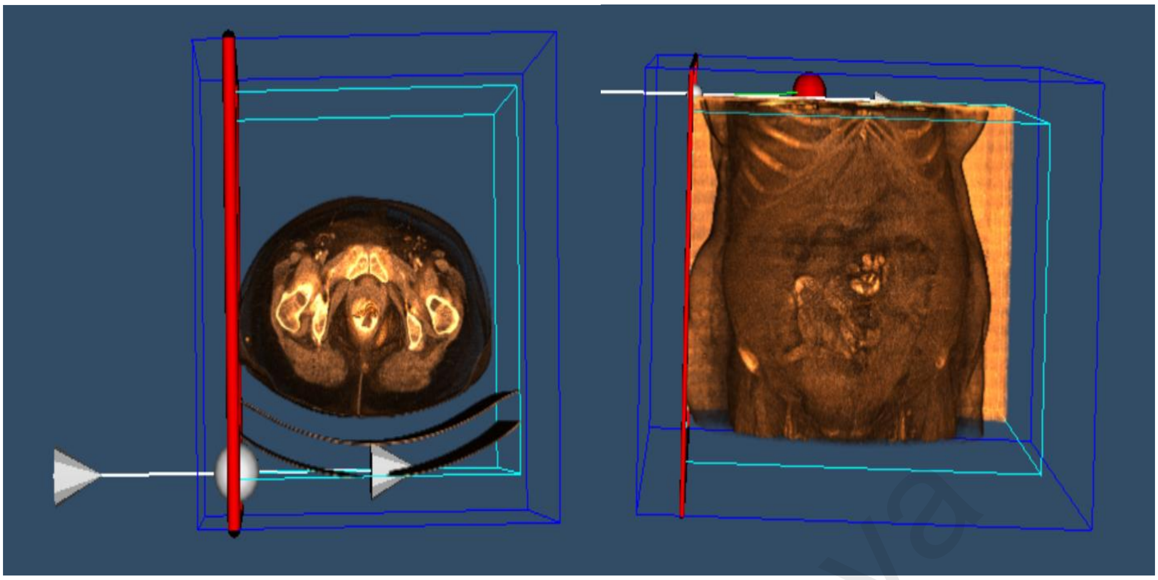

Figure 27 Method 4 (Volume rendering with additional feature) results (Left) top view, (Right) front view

Volume rendering (Method 3&4) effectively shows a result image of detailed tissues and bone structure, and hidden areas of interest with few artifacts (Figure 27,28,29). It shows 3-D relationships with varying degrees of success by using the degree of surface shading and opacity which cause the 3D images becomes more real “3D” through shading and opacity properties that was set to the volume. Method 3 implies the basic ray casting techniques where the opacity of each objects are took into account without any urgency being put into any of the structures. This in return produce of object will almost the same transparency if the state of the objects are the same for instance, skin will have the same opacity as there are both opaque objects. On the other hand, Method 4 is a the improvised version of basic ray casting, where selective opacity took place. In a more simpler term, improvised backward mapping are able to determine which structures supposedly to be highlighted, for instance in figure 28, the main focus of the image is brain and the forehead of patients is set to a transparent layer.

4.4 Additional features result in Method 4

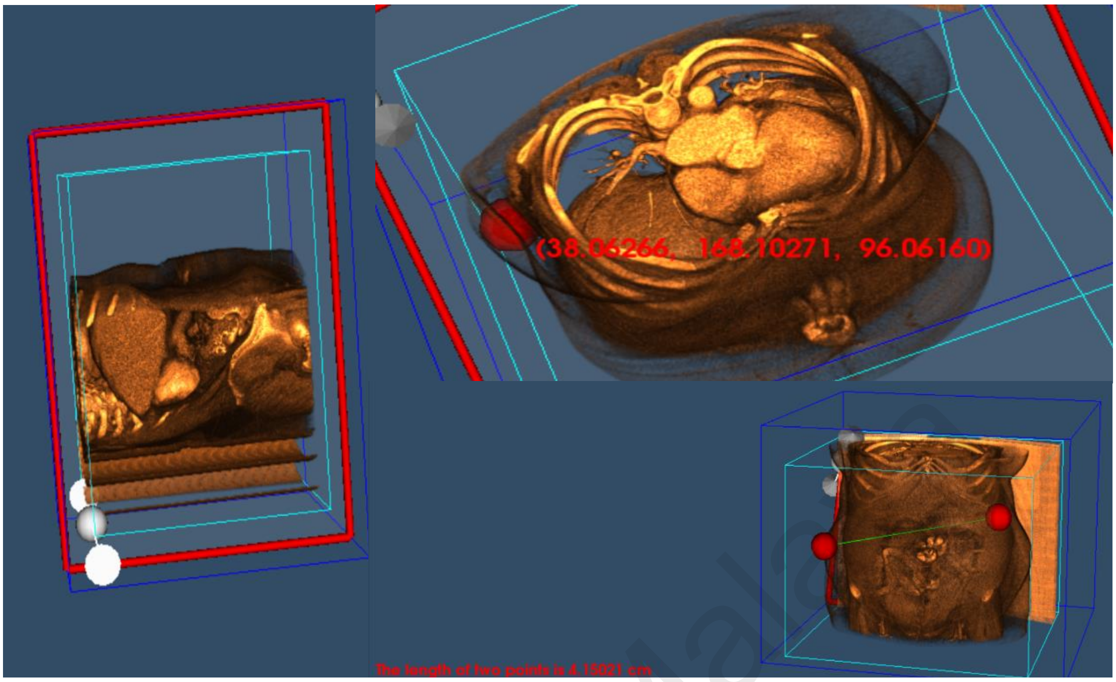

Figure 28 Method 4: New feature results (Left) crop feature (Right above), coordinate feature, (Right below) length measurement feature

Lastly, Method 4 shows the result of additional features for crop, coordinates and length measurement features. When the plane widget was resize it has the ability to crop the outer surface so the inner surface can be seen as shown in Figure 29 (Left) meanwhile if the mouse were clicked two times, the 2 spheres were shown and the coordinate of the clicked points will be shown as in Figure 29 (Right above). For the length measurement feature, if mouse is right clicked then the length between two points that were clicked will be shown Figure 29 (Right below).

CHAPTER 5: DISCUSSION

While surface rendering (Method 1) creates more three-dimensionally realistic images of the bone surface, it may be of limited clinical utility due to numerous artifacts and the inability to show lesions in abdomen and subcortical pathology in brain. Other than that, it uses a monotone colored approach and can only visualize the geometry features of an isosurface. The lack of the capability to illustrate the material property and the internal structures behind an isosurface has been a big limitation of this method in applications.

Meanwhile, volume rendering (Method 3&4) is effectively displays a variety of skeletal pathology with few artifacts. Relative voxel attenuation is represented in 3D through a gray scale or in color, and because one can choose which voxels to render opaque and which to render transparent, there is more information than surface rendering. Volume rendering maintains the anatomic spatial relationship of the CT data set and depth information, thereby better representing the interrelationship between vascular and visceral structures. Therefore, Method 3&4 is more suitable to have a clear diagnosis. However, it has some difficulty in interpreting the cloudy interiors. Therefore, high resolution 2D CT images and high RAM computer is needed to run this method in order to solve this problem especially when the number of 2D CT image slices is high.

In Multiplanar rendering (Method 2), the relationship of the organs to each other are shown in a different view along with a view of an entire tumor in another plane may help determine treatment options. Any of plane can be used to obtain the data. The main advantage of the multi-planar reformatting method is that one is not restricted to viewing in the direction the data was scanned, which makes it possible to visualize data that was measured in different slices in one two-dimensional image. The main drawback is that the visualized data is, like the original slices, two dimensional. A single image does not give much more insight in the three-dimensional structures than the measured slices.

However, it requires a lot of RAM in order to run this method. Therefore, it cannot be used in laptop and requires PC in order to have a high speed visualization. In addition, Method 1 and 2 3D reconstruction images can be improvised by increasing the contour value for human skin which is 500 and 1150 for human bone but this method only available by using high RAM PC to run the coding.

In order to have a more detailed pathology diagnosis, these additional features are important to view more details diagnosis. In the Method 4, Figure 29 shows 3 additional features which are crop feature that is helpful in viewing inner surface of abdomen that can help to determine lesions clearly. It will help to view more detailed diagnosis with a high speed visualization. Other than that, coordinate feature helps to state the coordination of the abdomen in which the user can use it to determine which part of the abdomen that have any lesions. Lastly, it also can measure the length between one coordinate to other coordinate which helps the user to determine the length of lesions and the user may be able to predict the size of lesions to plan the best treatment for the patient. Therefore, in this paper Method 4 shows the best method in diagnosing by visualizing clear 3D structures of abdomen by using volume rendering with additional features that help the user to have a detailed data from 2D abdominal CT images.

CHAPTER 6: CONCLUSION

In this research, four kind of different methods which are surface rendering, surface rendering with multiplanar rendering, volume rendering and volume rendering with additional features has been tested as a measure to produce a clear 3D models and structures of abdominal 2D CT images in order to ease the diagnosis of pathological formations and preparing the treatment plans. Through the experiment, it shows that volume rendering with additional features has advantage in reconstructing the meticulous tissues and bones of abdomen and helps in providing a detailed data by coordinate, measurement and crop feature in order to determine the exact coordinate for les located in abdomen, length measurement of the tumor and crop the outer surface of abdomen to see the inner surface of abdomen, respectively.

However, there is a limitation in this method since it will produce a few artifacts. Therefore, high resolution 2D CT images and high RAM computer are needed to run this method in order to solve this problem. VTK and C++ is an important tool in development medical 3D visualization software system. In the future, this technology may be the major tool for every hospital in order to ease the radiologists and medical doctor in diagnosing illness and make plans for the treatment quickly with a low budget. Therefore, in a future and advanced application, this advanced 3-D processing tools can be embedded into the diagnostic viewing application to allow efficient reconstruction of images, simultaneous comparison of 2-D and 3-D images, and referencing of historical data. This reduces costs and creates greater productivity and enhanced diagnostic confidence.

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