THREE-DIMENSIONAL VISUALIZATION OF BRAIN TUMOR COMPUTED TOMOGRAPHY IMAGES

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FACULTY OF ENGINEERING
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THREE-DIMENSIONAL VISUALIZATION OF BRAIN TUMOR COMPUTED TOMOGRAPHY IMAGES

SUMMARY

Open-source software used to reconstruct and visualize 3D image from 2D computed tomography (CT) images. This research used Visualization toolkit (VTK) and 3D slicer software to reconstruct 3D image from a set of 2D brain tumor CT image. Each software practiced four different methods to visualize 3D image from a set of 2D image. Methods used in VTK software are surface rendering, multiplanar rendering, volume rendering and volume rendering with additional features while 3D slicer software display surface of 3D model, multiplanar 3D model, volume 3D model and volume with measurement 3D model. A set of 2D brain segment images obtained from CT scan used as source data. The reconstructed 3D images expected to visualize 2D brain tumor CT images into 3D image and measure 3D volume of brain tumor. Result of 3D slicer will be used for comparison purposes. The result shows that both software capable to reconstruct and visualize 3D image from a set of 2D images. However, volume rendering with additional features method by using VTK shows the best result in reconstructing 3D image from a set of 2D images because of lower noise and artifacts present in the 3D image. Plus, the method able to crop the 3D image and allow user to observe cross-section of the 3D image for measuring the brain tumor size. In conclusion, 3D reconstruction software ease physicians and radiologists to diagnose abnormalities faster and precisely.

Keywords: Three-dimensional (3D) images, Brain tumor, Computed tomography (CT) images, Visualization toolkit (VTK), Rendering techniques

PEMBINAAN SEMULA TIGA DIMENSI KOMPUTASI TOMOGRAFI IMEJ BARAH OTAK

RINGKASAN

Perisian sumber terbuka digunakan untuk membina semula dan memvisualisasikan gambar 3 dimensi (3D). Penyelidikan ini menggunakan perisian Visualization toolkit (VTK) dan 3D slicer untuk membina semula gambar 3D dari satu set gambar 2D tumor otak. Setiap perisian mempraktikkan empat kaedah. Prosedur yang digunakan oleh perisian VTK adalah rendering permukaan, rendering multiplanar, isipadu rendering dan isipadu rendering beserta kaedah ciri tambahan sementara perisian 3D slicer memaparkan permukaan model 3D, multiplanar model 3D, isipadu model 3D dan isipadu 3D model beserta pengukuran. Satu set gambar segmen otak 2D yang diperoleh dari imbasan CT digunakan sebagai sumber data. Imej 3D yang dibina semula akan memvisualisasikan gambar CT 2D tumor otak menjadi gambar 3D dan mengukur saiz tumor otak 3D. Hasil perisian 3D slicer digunakan untuk tujuan perbandingan. Kajian ini menunjukkan bahawa kedua-dua perisian ini mampu merekonstruksi dan memvisualisasikan gambar 3D dari satu set gambar 2D. Walau bagaimanapun, isipadu rendering dengan kaedah ciri tambahan menggunakan VTK menunjukkan hasil terbaik dalam membina semula gambar 3D dari gambar-gambar 2D kerana terdapat bunyi dan artifak yang lebih rendah di dalam gambar 3D. Selain itu, kaedah ini membenarkan pengguna melihat keratan rentas gambar 3D untuk mengukur saiz tumor otak. Kesimpulannya, perisian pembinaan semula 3D memudahkan doktor dan ahli radiologi untuk mendiagnosis kelainan dalam badan manusia dengan lebih cepat dan tepat.

Kata kunci: Imej tiga dimensi, Tumor otak, Imbasan komputer tomografi, Visualization toolkit (VTK), Teknik persembahan

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LIST OF SYMBOLS AND ABBREVIATIONS

VTK	:	Visualization toolkit
3D	:	Three dimensional
2D	:	Two dimensional
CT	:	Computed tomography
SNR	:	Signal to noise ratio
dB	:	Decibel
SSD	:	Shaded surface display
MIP	:	Maximum intensity projection
MinIP	:	Minimum intensity projection

CHAPTER 1: INTRODUCTION

1.1 Background

Brain is stunning organ that consists of billion nerves that communicate in synapses (Bear, Connors, & Paradiso, 2020). Brain is powerful organ that able to initiate body movement and control human behavior. Plus, the organ is the seat of wisdom. Brain includes in nervous system that involve in interpreting information from five senses and control body function such as movements, speech and thought. Brain condition can affect memory, sensation and personality of human (Garcia, Archer, & Kostrzewa, 2019). Brain disorder is a condition that affect brain caused by injury or genetics. One of the brain disorders is brain tumor condition. Brain tumor is an abnormal condition of tissue growth inside the brain.

Physical examination and brain imaging are needed in diagnosing brain tumor. Patients with brain tumor receive treatments based on size of tumors, patients ages and health condition. Imaging method provide imagery of patient's internal and allow physicians to monitor brain condition for further treatment such as surgery. According to Veer and Patil (2015), scanning of brain can be done in many methods by using multiple techniques such as computed tomography (CT) scan.

CT scanner machine used in radiology for medical imaging (Shung, Smith, & Tsui, 2012). In general, it involves usage of computer and x-ray to obtain cross-sectional images of targeted body part. CT scanner is different from x-ray machine as it emits a series of radiation beam through human body that move through an arc and obtained different density level of targeted body part. The data of targeted body part transmitted to a computer and display it on the screen. Nowadays, spiral CT scan is widely used as it able to increase the accuracy and speed of the machine by collecting continuous data of targeted body part between images.

However, 2D CT images unable to quantify the volume of structure of target part in the body as the view is a 2D frame. Plus, usage of radiation has potentially harm patients by causing cancer or thyroid disease. Thus, CT scan is only allowed for patients with clear medical reason. Besides, volume of structure needs to be quantified for monitoring the development of tumor and identifying the response rate of specific treatment.

Advancement of medical imaging method and technology allow 3D images reconstruction from 2D images. According to Warren, Patronas, Aikin, Albert, and Balis (2001), software for 3D reconstruction is widely accessible and able to measure volume of irregular shaped tumors. Hence, the technology being used in many healthcare facilities around the world as it provides high quality of 3D images. The 3D images provide good imagery of internal organs and assist physicians in planning treatment for patients. Thus, 3D reconstruction refers to 3D images formation that used 3D rendering software in generating a dataset of 3D images from multiple 2D images.

Based on standard protocol of 3D reconstruction, the 3D images will be returned to the picture archiving communications system (PACS) and linked with source images. Rendering techniques play important role in allowing visualization of 3D images information. Apart from that, surface, volume and multiplanar rendering are primary techniques of rendering for creating a dataset of 3D images.

This research used a set of 2D brain tumor images obtained from CT scanner. Then, visualization toolkit (VTK) with C++ language and visual studio 9.0 software used to reconstruct 3D images from the multiple 2D brain tumor CT images. Developers allowed to have the coding and change it to fit their demand using C++ language. The research aims to develop a program that able to visualizes 2D brain tumor CT images in 3D formation.

1.2 Problem statement

CT scanner produce two-dimensional images of brain that used for observing condition of the brain and allow physicians to overview the whole brain. However, 2D image has limitations to display internal structure of the brain tissue and lesions accurately because of height and depth of 2D images cannot be evaluated. Plus, CT machine produce a set of 2D images has limitation to quantify volume of brain and brain tumor structures. It needs appropriate software to reconstruct and display clearer 3D images.

1.3 Aim and objectives

The aim of the research is to develop a program that able to visualizes 2D brain tumor CT images in 3D formation. There are three objectives of this study.

a. To visualize two-dimensional brain tumor CT images into three-dimensional images using visualization toolkit (VTK)
b. To measure 3D volume of brain tumor using visualization toolkit (VTK)
c. To compare 3D reconstruction results between VTK and 3D slicer software

CHAPTER 2: LITERATURE REVIEW

2.1 Computed tomography (CT) scan

Computed tomography (CT) is a diagnostic medical imaging device that used x-ray tomographic technique to generate cross sectional images of patient. Image reconstruction uses CT raw data to calculate local attenuation at each point within acquisition volume to yield CT number for every point of the image matrix and finally converted the CT images data into gray shades image. The CT scan produces detailed images compared to X-ray images. The machine used to obtain image of soft tissues, blood vessels, bones and internal organs. Plus, it helps in identifying location of tumor in the organ. According to reconstruction increment, 2D images separated with equal length gaps during the process. Calibration is an important safety procedure in handling machines. CT scan have several calibration methods. Three latest common calibration methods used for calculating dose for a range of CT conditions used vendor provided method, relative to 120kVp CT spectrum and relative to megavoltage beam (Scarboro et al., 2019).

2.2 Two-dimensional (2D) and three-dimensional (3D) images

Usage of 2D and 3D images in medical field help physicians and health professionals in exchanging clear information. The main difference between 2D and 3D images are the depth of the image. 2D image has no depth information causing misinterpretation complex structures while 3D image contains depth and volume information. Consequently, 3D imaging own advantages over 2D imaging as viewer able to visualize and observe the depth of the image. Plus, 3D images of structures in the living body aid viewers to visualize and measuring the structure directly from 3D data set. In general, 3D visual aids exist in the form of photographs, interactive computerized models and volume rendered models that created from 2D scan images while 2D visual aids present in the form of photographs, illustration and scans (Ballantyne, 2011).

Hence, better medical decision can be made by observing structures in the body from 3D volume rendered models. Nowadays, there are many materials and imaging techniques can be used to build 3D models. At this time, 3D reconstruction from 2D scan images was done by using imaging software.

2.3 Three-dimensional (3D) Reconstruction

A set of images used in 3D reconstruction to create three dimensional models. A single 2D image has lack of information to reconstruct 3D image as the depth of object is loss during image formation from 3D object into 2D image. Thus, multiple images input commonly being used for 3D reconstruction.

There are two important elements in an image which are pixels and voxels. Pixels is picture elements in 2D image while voxels are volume elements that produce volume in a picture. On top of that, a volume of data can be extracted from 2D images obtained from CT scan and the length gaps filled by interpolation during 3D reconstruction process.

2.3.1 Data Acquisition

Data collected are grey shaded 2D images of 3D scene taken with CT scan. Radiologist usually work with technologist in developing imaging protocol during data acquisition. The images contained pixel value of ray illuminated to the point of the scene.

2.3.1.1 Pixels and voxels

(a) **Pixels**

Pixels is a building block that build a digital 2D image on screen. It is a digital graphic that has smallest unit and displayed as square on screen of devices such as television, monitor and handphone. Size of pixels in an image calculate as pixels per inch (PPI), play important role in controlling the quality, resolution and color of a picture.

Lower density and number of pixels produce higher resolution of an image and vice versa. Size of pixels display on the screen shows as figure below.

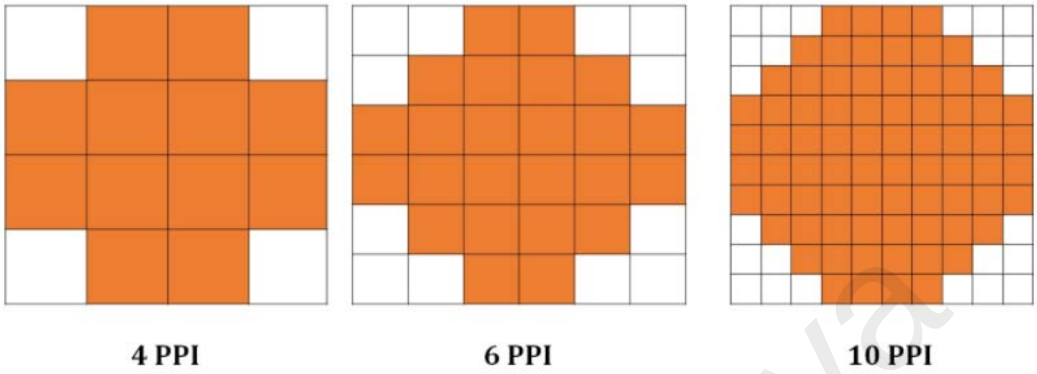

Figure 1 Size of pixels

(b) ***Voxels***

Voxels can be described as volumetric information as it gives value on a grid in 3D space. Plus, voxels have volumetric pixels that aid in building 3D scene. 2D image turned into 3D image with projection of the voxels data as voxels builds volume on the surface of 2D scene. In other words, voxels give shape and size of 3D object in many forms such as pentagon, octagon, rectangle and spherical. Figure below shows voxels form a square.

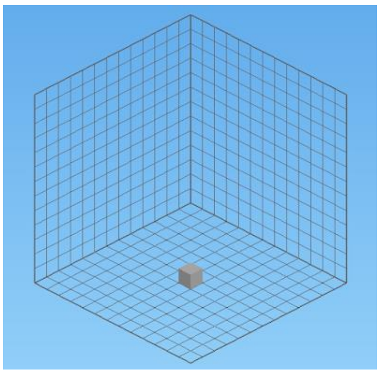

Figure 2 shows voxels form a square. Voxels present in the same size and combined on the same grid at different positions in order to build voxels model such as square.

2.3.1.2 3D shape extraction

Two main methods in 3D acquisition are given in Figure 3, which are active and passive methods. Active method involves controlled light source to achieve 3D information while passive method involves uncontrolled light source to obtain 3D information. Plus, common passive technique used available ambient light for arriving the information during capturing process.

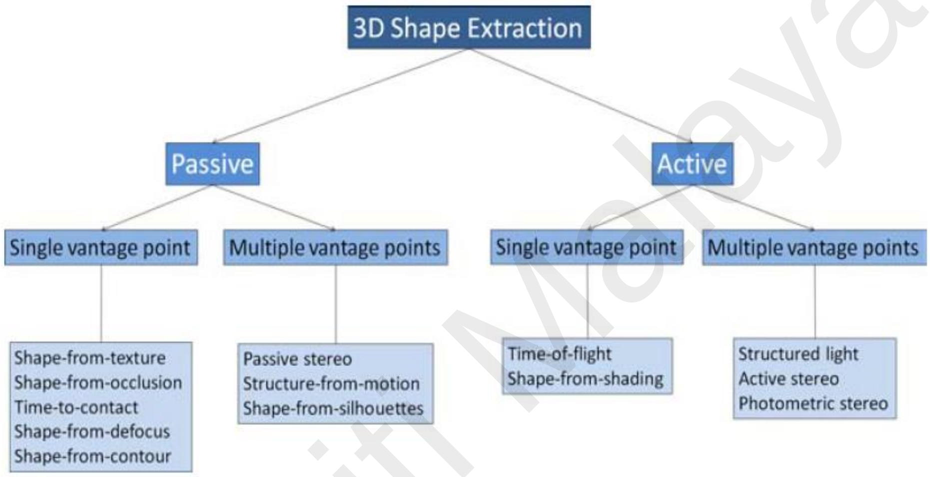

Figure 3 Three-dimensional acquisition methods

There are several numbers of vantage points from the illuminated scenes during 3D shape extraction, single vantage point and multiple vantage point. Single vantage points usually involve a single viewing in the system. However, there are cases where a single vantage point involves multiple illumination components and these components positioned very close to each other and coincide. Multi vantage point involve several views in the system and the multiple illumination components need to be positioned away enough from each other in order to allow systems to work properly. Thus, single vantage points method has upper hand as the components can be made compactly and restrict issue such as invisible scene from vantage point.

2.3.1.3 Triangulation

Triangulation principle used to extract depth information. Passive triangulation explained two projections of similar point onto two images. The images take at the same time with different viewpoints. 3D position of the scene obtained by identifying the intersection of the projection rays.

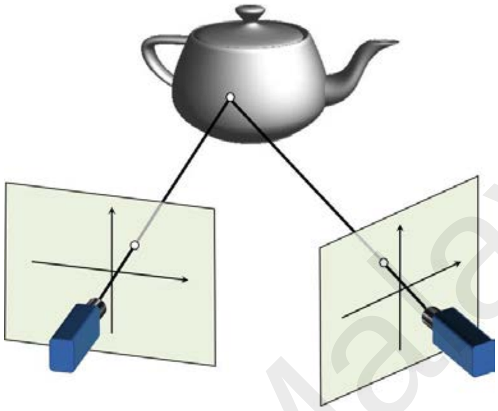

Figure 4 Passive triangulation

Combination of illumination source such as laser with one camera able to facilitate the finding corresponding points. The projection device allows targeted spot to be detected easily by the camera. 3D surface point is about intersection of laser ray and camera ray. This setting called as active triangulation.

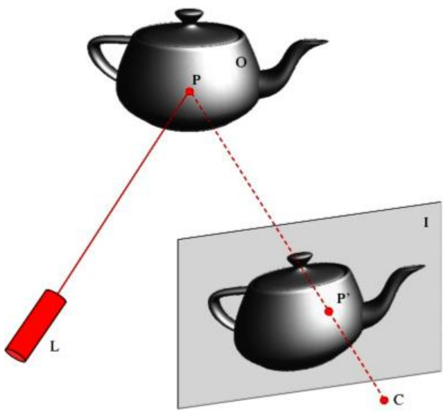

Figure 5 Active triangulation

However, 3D coordinates of the targeted point difficult to be detected. Thus, illustration ray such as laser ray often directed on different points of the surface and image taken on each of the point in order to extract 3D coordinates of the points.

2.3.2 Pre-processing of data

Collected data will be processed by removing the noise in the 2D images and the resolution of the 2D images will be improved in order to have better quality of image.

2.3.2.1 Resolution

Number of pixels per inch (PPI) of an image determine the resolution of an image. The quality of an image depends on the resolution value. High resolution of image result in high quality of image vice versa. Pixels carry information to describe the image. Thus, number of pixels play important role in determining the resolution and quality of an image. The higher number of pixels, the smaller size of pixels in an image causing higher resolution of an image vice versa. Figure below shows an image with higher and lower resolution.

Figure 6 shows resolution of images. High quality of image has high resolution (a) while low quality of image has low resolution (b)

2.3.2.2 Noise

Noise presents randomly in digital images will lowering quality of the image. Sometimes, noise needed for producing grainy look images. Degree of noise can be controlled by adjusting setting in the camera such as length of exposure and temperature level. Noise in an image is unavoidable. Signal to noise ratio (SNR) is an useful measure in science and engineering that compare desired signal level to the background noise level (Gragido, Pirc, Selby, & Molina, 2013). SNR categorized as universal way in comparing the level of background noise and desired signal for a device. Decibels (dB) is unit of expression for measuring the SNR. Camera image with high SNR allow separation of background noise with image information while low SNR causing difficulties in separating image information with background noise. Figure below shows images with high SNR and low SNR.

Figure 7 Image with high SNR

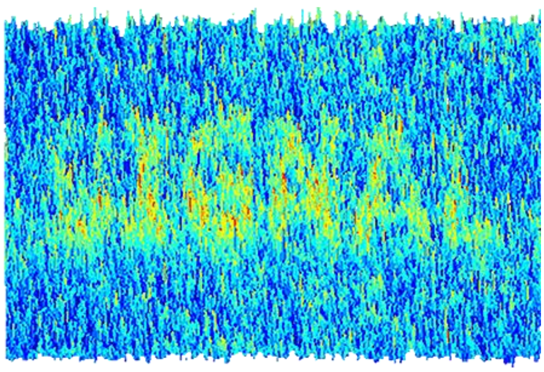

Figure 8 Image with low SNR

2.3.3 Volume reconstruction

Volume reconstruction is the main part of 3D reconstruction. Interpolation, conversion algorithm and ray casting process implemented to obtain 3D volume information from 2D information and placed in volume grid based on spatial data without losing important data. Thus, coordinate system and volume grid such as size of the volume and axis for origin determined before starting volume reconstruction. Principal component analysis (PCA) is a technique used to reduce variables in data set while protecting and maintaining important information (Abdi & Williams, 2010). In addition, PCA used for configurating volume coordinate follow by volume reconstruction. Next, volume reconstruction can be continued by using 3D reconstruction software such as VTK and 3D slicer software.

2.3.3.1 Interpolation

Interpolation is an important process in reconstructing 2D image into 3D image. This process can be described as procedure of calculating unknown values using available known points (Zhang & Wu, 2008). Each location predicted to has value of their own called as interpolated value (IV). Linear interpolation and natural neighbor interpolation are popular interpolation's technique for 3D reconstruction. Figure below shows that interpolation aid in filling the unfilled gaps of data of an image. The data made of voxels units.

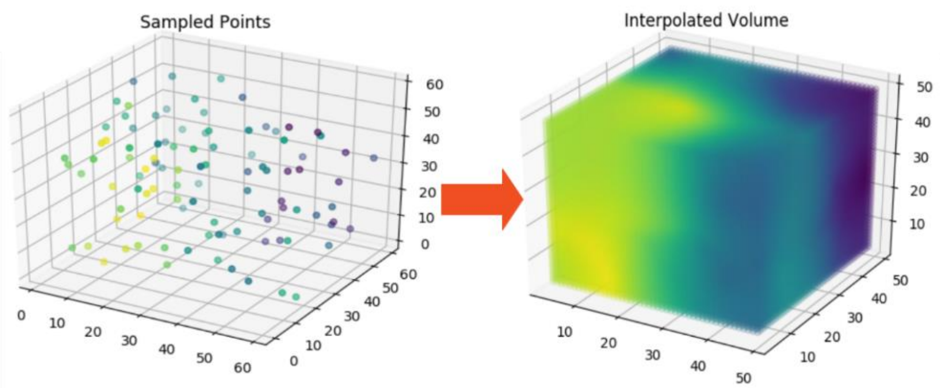

Figure 9 Interpolation

(a) Linear interpolation

Linear interpolation method is a procedure of estimating unknown values using interpolated value gained from linear relationship between two adjacent point. In addition, each position of the point calculated based on graph formed by this process using mathematical formula:

$$y = mx + c$$

(b) Natural neighbor interpolation

The main keywords of natural neighbor interpolation are data fitting and smoothing (Dinis, Jorge, & Belinha, 2007). Mathematical tools used for obtaining points of natural neighbors for each node that is property to the global nodal set are using Voronoi diagram and Delaunay triangulation. This method suitable to a dimensional scene and scattered data.

2.3.3.2 Conversion algorithms

Algorithms of 2D to 3D conversion requires sets of data. Number of input images play important role in categorizing algorithms. Multi-ocular depth cues involve two or more input images obtained by capturing pictures of the point from different location using multiple fixed cameras or capturing pictures of moving object in the scenes using single camera. Monocular depth cues operate algorithm with single image.

Table 1 Summarization of depth cue used in 2D to 3D conversion algorithm

Number of input image	Depth cues
Two or more image	Binocular disparity Motion parallax Image blur Silhouette
Single image	Linear perspective Atmospheric scattering Shape from shading

(a) ***Binocular disparity***

Depth of a point on the images can be obtained using binocular disparity. Different image locations of the same scene captured to extract depth of a point on the images.

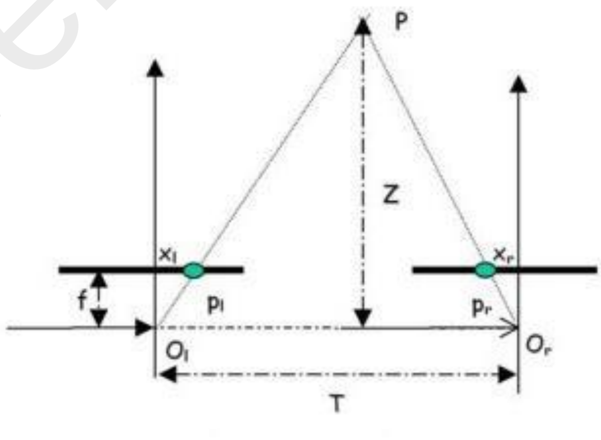

Figure 10 shows two different projections of point P on image of P1 and Pr. O1 and Or explained the coordinate of two cameras

Thus, relationship between the depth Z of the point P and the triangle describe as formula below:

D = xr – x1

Z = fTD

(b) ***Motion parallax***

Size of an object increase due to object changes in position moving across the retina of a moving person. The nearer the position of an object to the observer, the faster and easier for the object to be out of the frame. Motion parallax can be described as a situation of a subject to an observer appear to move greater amount when they are at a smaller distance and vice versa (Brinkmann, 2008). For example, when we ride a car and look outside the window, a house by the side of the highway disappeared from our sight faster compared to a distant mount by the side of the highway. Both mount and house are standing still but the amount of distance are different.

According to Brinkmann (2008), This phenomenon occurred due to the amount of distance the object and observer compared with the percentage of the field of view.

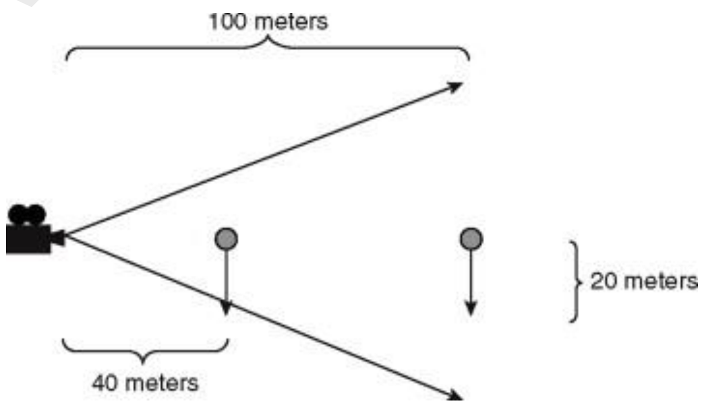

Figure 11 shows the object with 100m away is moving 20m downward and still located in the observer's field of view while the object with 40m away is moving with the same displacement disappeared from the field of view

(c) Image blur

Image blur used as an effective cue to depth (Mather, 1997). Blur variation between image region shows that the region is located at different depth. Object that clearly captured is in focus while the blur region is defocused at different distance. According to Mather (1997), depth perception depended on the range of visual cues including size and texture gradient of an object.

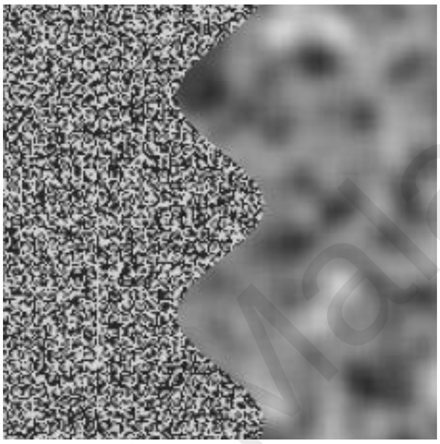

Figure 12 shows focused region present with sharp texture and sharp edge compared to defocused region

(d) Silhouette

Silhouette image can be explained as segment foreground object from the background (Yang, Gonzalez-Banos, & Guibas, 2003). Multiple input image taken from different viewpoints. In addition, background subtraction used to segment the target object and back projected to 3D scene in order to retrieve silhouettes. Reconstructing a 3D object based on 2D silhouette object used to neglect some features of the surface. The 3D reconstruction technique described as shape-from-silhouette.

2.3.4 Volume visualization

Volume visualization is a step to display volume data on 3-dimensional grid after volume reconstruction. The step is to allow result observation by user. There is several software that can be used to for this step. For examples visualization toolkit (VTK) and 3D slicer. Both are common software that being used for volume reconstruction and visualization. Volume visualization aid in diagnosis of disease as it helps specialists in observing scanned area. This stage includes several rendering methods such as multiplanar rendering, volume rendering and surface rendering (Mohamed & Siang, 2019). In addition, volume rendering can be applied for giving color during visualization and allow user to visualize the object transparent, semi-transparent or opaque. Plus, volume rendering able to be done in many ways depending on conventional computer graphics and it also able to share rendering methods such as shading or blending (Meibner, Pfister, Westermann, & Wittenbrink, 2000).

2.3.4.1 Surface rendering

Shading enhances the performance of images that visualize in computer graphics. It gives shadow effects on an object that is rendered. Surface rendering is rendering surface using shading model method after using surface primitive to fit iso-surface inside a volume data (Blezek, Yang, & Erickson, 2009). Surface rendering also called as shaded surface display (SSD) represent structure surface of the object. The surface of structure can be seen by estimating the surface based on data of image given. Pre-processing step is one of the main steps in surface rendering. It involve determination of surface based on image given and possible to devise a processor for volume rendering (Udupa, Hung, & Chuang, 1991). Last, surface rendering play important role in shaping the entire structure of 3D model.

2.3.4.2 Volume rendering

This technique allows users to understand volumetric data in 3D scalar field. Volume of images created by imaging a series of cross sections (Drebin, Carpenter, & Hanrahan, 1988). Volume rendering involve volumetric grid and data. Regular volumetric grid is a region where voxels of images are sampled in order to obtain volumetric data and create representative value for the region. Plus, volume rendering involves opacity of each voxel. According to Kindlmann, Whitaker, Tasdizen, and Moller (2003), transfer function has data on the base image where the data applied as input opacity value onto each volume and identify resulting image transparency. In addition, 2D projection based on 3D data set obtained from medical scanner device such as CT scan. It is necessary to have images from different angles and views in order to create and see the volume. On top of that, position and location of camera need to be identified to obtain volume dataset, then each voxels color and opacity have to be determined. Ray casting principles applied in this technique, each pixel on the plane illuminate a ray and intersecting with voxels, then the information obtained.

(a) ***Ray casting***

Ray casting is foundation of computer graphic rendering algorithm that implemented in volume reconstruction. The process involves conversion of limited data into 3D projection by using geometric algorithm of ray tracing from the screen into volume view. In general, ray casting used voxels unit to build volume and forming 3D image on the screen. The projection of volume on the pixel's screen is not same as projection of volume on the flat panel. Thus, interpolation technique needed to form the rays in order to fill in the values of the missing points and project volume's voxels. Figure below shows ray casting. The ray cast through pixel's screen, then to the viewing volume and integrate information by illumination (Ljung, 2021). The information of the points along the ray value stored in pixels.

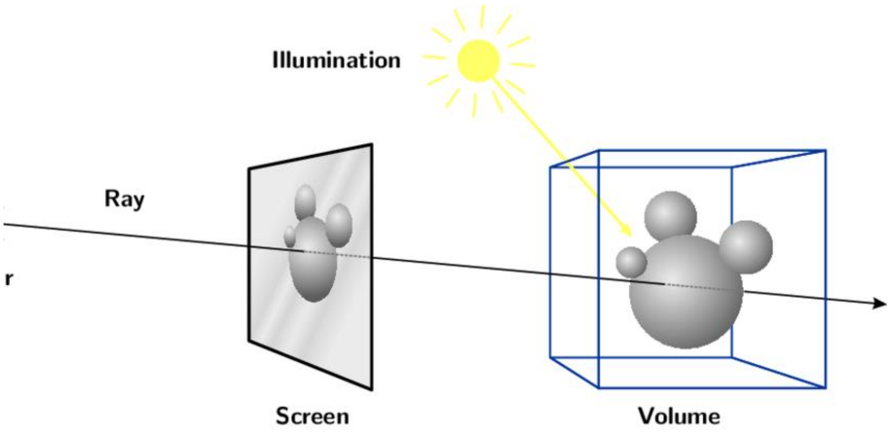

Figure 13 Ray casting

(b) Maximum intensity projection (MIP)

Maximum intensity projection is a rendering technique that has highest attenuation value in projected voxels onto a 2D image. This technique used to extract vascular structures from medical data set to create angiographic images as the highest voxel attenuation values used to rebuild the image. In addition, Minimum Intensity Projection (MinIP) produce image with lowest pixel value. Thus, highest value of interpolated voxel along the projected ray is same with MIP image pixel value while pixel value of MinIP images equal to lowest interpolated pixel value along the projected ray (Luccichenti et al., 2005). MIP image result in superimposing hyperintense structures and voxels are projected onto 2D image.

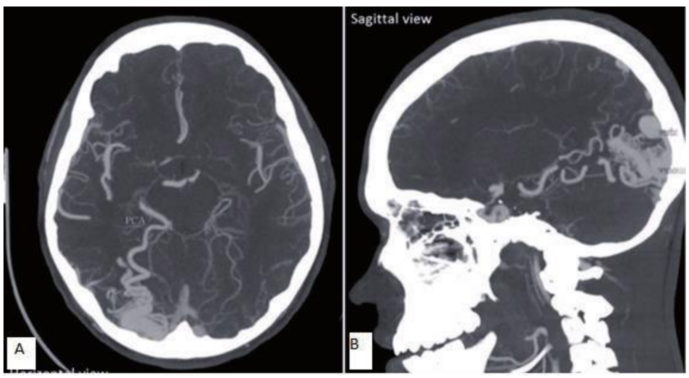

Figure 14 MIP axial and sagittal view of CT head angiogram (Ganaw et al., 2019)

2.3.4.3 Multiplanar reformation

Multiplanar reformation is a process of transforming data from imaging modality in a plane into another plane to produce good anatomy portray. For example, a set of data from axial CT images convert into axial and non-axial plane such as coronal and sagittal plane.

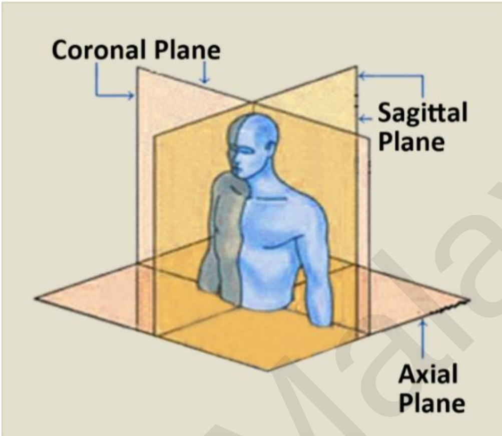

Figure 15 Example of non-axial planes

The data can be manipulated and reformatted to enhance structure of sample by using available software. MPR process creates spatial distance between structures on each plane. MPR images are thickening into slab when pixel values in the reformatted planes are interpolated from voxels.

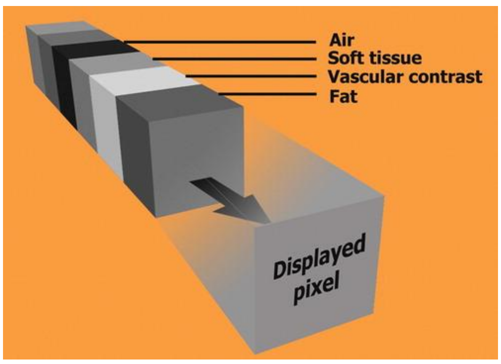

Figure 16 shows processing data encountered when ray passes through the stack of reconstructed section along the line of sight (Dalrymple, Prasad, Freckleton, & Chintapalli, 2005).

2.3.4.4 Classification and segmentation

Classification of image play important role in medical image analysis. It provides structured framework to volume data and accept input parameters such as characteristics of sample in order to ease analysis of images and enhance performance of the images. For example, classification process gives color and opacity input to the sample in order to enhance the performance of structure. According to Meibner et al. (2000) classification aid in finding structure within volume data. It gives permission in observing inside structure of the sample. However, it might fail in allowing user to observe certain structure of the sample especially while obtaining volume data of different types of tissue from CT scan. This is because of same density values between different types of tissue. Thus, structure with same density values needs to be differentiated by segmenting the structure.

2.4 3D reconstruction's problems

Calibration problem during image formation should be known. Camera play important role in the formation of images. Camera's intrinsic parameters such as focal length, center of image and position of the camera are crucial information to identify coordinates and orientation of the scene. Extrinsic parameter of the camera is determining coordinates of the scene that unlinked to the camera by knowing position and orientation of the cameras. Both parameters are considering as calibration parameters that should be confirmed. In addition, matching problem should not be neglected where the ability to identify and link the scene on pictures obtained is a must. Plus, reconstruction problem should be asked in determining 3D coordinates of the scenes from both calibration parameters. The coordinates used to visually define shape of object. However, the coordinates are causing the reconstruction to sparse if the surface where the points belong were undefined to determine a mesh or a dense model.

2.5 Clinical application of 3D reconstruction

Main limitation of 2D CT image is unable to define accurate boundary of each organ and differentiate tissues with same density values. 3D imaging help radiologists and physicians to visualize and analyze diseases inside of body accurately by separating organs and minimizing overlying tissues.

2.5.1 3D brain tumor images

Brain tumor is difficult treat disease. It can be cancerous or non-cancerous. In addition, pressure inside the skull become worse when the size of brain tumor increase. Currently, surgery is common treatment that use to remove tumors from brain without causing injury or lesion to healthy section of the brain. However, all treatments have potential for risks and complications. Precise information of tumor’s condition are necessary during operative and preoperative planning phase (Mert et al., 2012). Surgeon need information such as location, size and type of tumor inside the brain to determine maximum limit for safe removal of tumor.

3D reconstruction is crucial method in providing information of the brain. It provides clear image of brain structures and differentiate tissues inside the brain. According to Mert et al. (2012), 3D brain surface visualization is clinically reliable for preoperative tumor localization compared to 2D brain images. As a result, surgeons able to minimize risk potential and complication after brain surgery such as brain damage, brain swelling and infection. This is because of accurate information help physicians and surgeons in making wise and precise decision during surgical planning. Other treatment such as chemotherapy can be combined with the surgery treatment based on patient’s condition.

There are three type of brain tumor which are benign, premalignant and malignant (Nanware, Taras, & Navale, 2020). The most harmful tumor is malignant as it is cancerous and grow actively to other body parts. Benign is not cancerous and barely grow to other part of body while premalignant has potential to become malignant tumor. Thus, it is necessary to monitor the tumor if there is any growth occur. 3D visualization produces clearer images of structure compared to 2D images. Hence, the 3D images possible to determine any changes in the brain tumor.

3D images have better spatial resolution allow physicians to monitor tumor effectively (Zelenak, Viera, & Hubert, 2013). Plus, rendering techniques during 3D reconstruction from 2D images capable to enhance structure of images (Barry et al., 1997). The visualization of structure and differentiation between tumor and other internal body parts enhanced by adjusting level of contrast, resolution and noise of images during rendering techniques. Next, 3D software application able to allow imaging the spatial configuration of white matter structure of the brain such as corpus collosum (Zelenak et al., 2013).

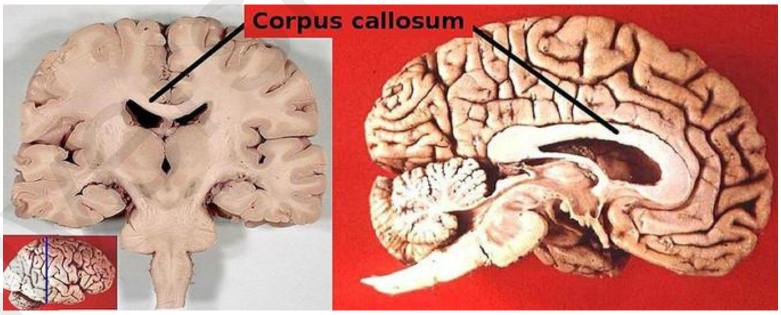

Figure 17 shows corpus collosum or called as white matter structure. The structure consists of glial cells and myelinated axons. It is white in dissected brain

2.6 Application of 3D reconstruction

Application of 3D reconstruction exists in many fields such as engineering, medicine, technology development, gaming and other virtual environments. In medicine field, usage of high radiation doses during imaging technique might harming patients with certain diseases and not advisable for those with ferromagnetic metallic im-plants. Consequently, 3D reconstruction plays important role in therapeutic and diagnostic purposes by producing 3D models from 2D images at multiple angles. In addition, 3D reconstruction offers additional diagnostic information without additional cost can be helpful in the characterization of the images. In robotic engineering field, 3D reconstruction applied for mapping and real time processing of 3D environment. The information used to predict available space, to find ways and avoid hurdles in the path. In addition, alternative method in mapping is using multiple result images of drone and 3D scene reconstruction to estimate dimension of the target area accurately and allow identifying small objects. Furthermore, there are many open-source software that can be used for 3D reconstruction from 2D images such as visualization tool kit (VTK) and 3D slicer software.

2.6.1 3D slicer

3D slicer is one of the biomedical application software that used in dealing and improving medical image computing. In addition, this software is categorizing as open-source software. 3D slicer can be used for displaying 3D view, real-time 3D ultrasound reconstruction and interacting with virtual reality using SlicerVR extension. There are many features available for users such as modules, extensions, suggestions, pull requests and datasets. In fact, 3D slicer allow user to install over 150 extensions. The software allow user to use phyton scripting and it is 3D printing friendly. Furthermore, 3D slicer supports wide range of information such as 2D, 3D, 4D images data and DICOM information.

Major different between VTK and 3D slicer is coding or algorithm. 3D slicer needs no operator to handle coding or algorithm while VTK is vice versa. User of 3D slicer able to easily insert data in any format such as JPEG file, DICOM file and PNG file.

2.6.2 Visualisation tool kit (VTK)

Open-source software allow user to access freely. Visualization tool kit is one of the open-source software that allow user to access it freely for 3D computer graphics, modelling, image processing, image visualization, rendering and 3D reconstruction. In addition, VTK supports many types of visualization algorithms and has several features that allow advance modelling techniques. Plus, it designed to run on any platform such as Windows, Mobile devices, Mac and Linux. In order to maximize efficiency of this software, the core function is written in C++.

Basic process of VTK start by inserting information of the source called as vtkSource information. The source data play important role in generating data layer. Then, the vtkSource filtered with vtkFilter to extract the dataset and equate attribute data from selected dataset. Next, vtkMapper derived from vtkObject specifies interface between the data and graphic primitives by different filtering process. The filtering process of vtkMapper convert geometric data into interface between original data and image data.

The step followed by rendering scene where vtkActor uses Mapper result to represent an object during rendering scene. Plus, vtkProperties represent lighting and surface properties of the object will be used to manipulate properties of image displayed. Last, image visualize on a screen. Thus, vtkRenderer used to finish the process by supplying an abstract specification for renderer during the rendering process. Render window play important role in attaining interoperability between displayed image and user.

2.6.3 Visualization toolkit program

Contour filtering and marching cube algorithm are techniques used to build surface of 3D image. Hafizah, Kok, and Supriyanto (2010) found that marching cube algorithm reconstructed clearer 3D images compared to contour filtering as it created higher intensity 3D image which ease user to identify internal organs and tissues based on 3D model. However, marching cube algorithm creates a triangle mesh which causing problem of duplicating memory storage. The triangle mesh used more memory spaces and affect display speed (Wee, Chai, & Supriyanto, 2011).

The marching cubes algorithm required extra process to minimize time and improve storage structure to reduce usage of storage and fasten display speed for reconstructing a surface from large volumetric data. Subsampling or minimizing volumetric image size usually applied to solve the problem but the quality of 3D surface will be reduced. A process which based on a pipeline of VTK can be used to increase the quality of 3D model's surface from sampled volumetric data (Narkbuakaew et al., 2008). Previous study shows that surface rendering method applied for surgery simulation by using VTK library as it allows users to determine appropriate plane of images based on 3D model (Wee et al., 2011). Surface rendering by VTK programmed with C++ language shows that the technique give desired effect of 3D reconstruction and the display time of the program is only 8.4s (Hong, 2014).

CHAPTER 3: METHODOLOGY

Two crucial steps for 3D reconstruction are 2D image acquisition and image processing. Open-source software involved in this research during image processing are Visualization toolkit (VTK) and 3D slicer software. There are four rendering methods used in this research which are surface rendering, multiplanar rendering, volume rendering and volume rendering with measuring features.

A set of 2D brain tumor images used for this research obtained from CT scan. There are 26 slices of 2D CT images of brain tumor involved in this research to reconstruct into 3D images. Resolution of each layer of image is 1012 X 706. Images file format used in this research is Joint Photographic Expert Groups (JPEG) format.

3.1 Rendering process using Visualization toolkit (VTK)

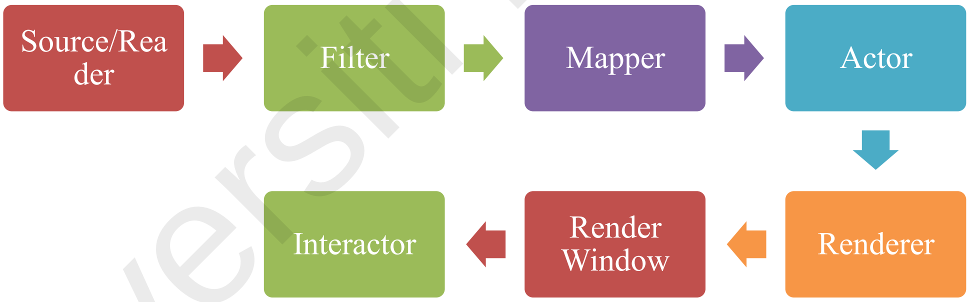

Figure 18: Pipeline for rendering

a. Source/Reader

A set of 2D brain tumor CT images is input data for this program. The input data read by reader which is 'vtkJPEGReader' in VTK. The reader used to read a series of 2D brain tumor image as a volume.

b. Filter

Input data received by filter which then the data altered into suitable data for a clear 3D model of brain tumor. Then, the modified data returned and passed to mapper.

Figure 19: Inheritance diagram for filter in VTK

c. Mapper

Function 'vtkPolyDataMapper' used in the VTK program to map the polygonal data to graphic primitives which forming rendering primitives. Function 'vtkMapper' is to identify and specify interface between data set and graphic primitive. The mapping controlled the creation of rendering primitive by providing a lookup table and determining a scalar range to map the data.

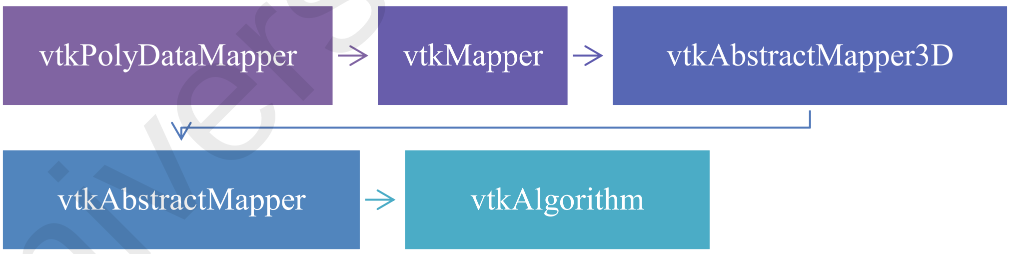

Figure 20 Inheritance diagram for vtkMapper

d. Actor

Function 'vtkActor' play important role in rendering scene by representing the structure. It consists position, orientation and features values to visualize the structure.

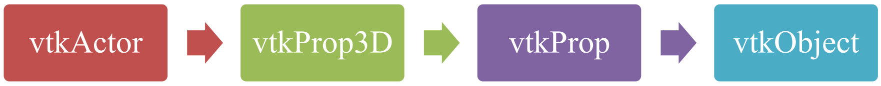

Figure 21: Inheritance diagram for vtkActor

e. Renderer

Rendering is a process of image formation by translating geometry, light information and camera view into an image. Function 'vtkRenderer' come up with abstract requirements for renderer. It involves in transformation of world, view and display coordinates. View coordinates is coordinate values of computer graphic rendering system while display coordinates is screen coordinates on output device.

f. Render window

Function 'vtkRenderWindow' applied to specify the characteristic of rendering window. It creates a window for renderers to draw 3D model.

Figure 22: Inheritance diagram for vtkRenderWindow

g. Interactor

Interactor allow interaction between mouse, keyboard and events in the scene display on the screen. Function 'vtkRenderWindowInteractor' prepares a platform-independent interaction with scene which allow user to control the visualization such as rotate and zoom.

3.2 Rendering Methods using VTK

3.2.1 Method 1: Surface rendering

Renderer created with function ‘vtkRenderer’. Then, the renderer portrayed into the render window with function ‘vtkRenderWindow’ which then interaction between mouse, keyboard and data of the structure within the window was allowed by using function ‘vtkRenderWindowInteractor’.

Based on the pipeline mechanism explained in figure 1, vtkJPEGReader used as reader to read a set of 2D brain tumor CT images as volume. Set data extent determine the dimension and position of images in each axis (x, y and z). The x-values and y-values based on dimension of images (1012 X 706) and z-values based on number of slices usedfor 3D reconstruction which is 26 slices of images. Thus, size of pixels in x-direction wasset as 0, 1011. Size of pixels in y-direction was set as 0,705 while size of pixels in z- direction was set as 1,25. Next, set file prefix determined the file location of dataset usedfor the program. Set data spacing is voxel values for the dataset in x, y and z-direction. Set origin determined the position in 3D space of first pixel point which is (0, 0, 0).

Then, filter was created to have smooth and clearer structure. Volume dataset of two iso-surfaces which are bone and skin structure were set based on ideal value. However, the value was set lower than ideal value due to low RAM PC.

In this method, ideal contour value for skin is 500 but contour value set for skin is 20.then, function ‘vtkPolyDataNormals’ filter created to smoothen surface shading during rendering. Then, rendering process speed up by creating function ‘vtkStripper’ as it buildstriangle strips from the iso-surface which result in faster rendering process.

After that, property of the skin such as color, opacity, specular power of the skin created.The skin color set by using RGB color range mode which 0 is black and 1 is white. Lowerspecular value causing small specular reflections and vice versa. The opacity was set between range 0 to 1 which 0 is transparent.

Next, same coding line used for bone structure but different volume dataset used for bone. Ideal contour value for bone is 1150 but contour value set for this method is 200. Feature angle for skin and bone set as 60 which the filter used to create sharp edge.

Then, color of bone set by using RGB color range mode. Function 'vtkOutlineFilter' created to build an outline which provides context around the data volume. The outline color created by using RGB color range mode which this method used 0.0 (black) to create black outline.

Function 'vtkCamera' build initial camera view to place the camera in certain direction. The position of the camera allow user to look at the data in the specific direction. Dolly method play important role in creating distance of camera towards focal point and allow zoom in and zoom out features.

Next, background color of the visual set by using RGB color mode and the renderer size set up based on pixel size. Last, solution of the VTK program will be configured or build to create visual studioproject files. Then, the file will be debugged to view the result.

3.2.2 Method 2: Multiplanar rendering

Method 2 starts with creating renderer which then draw into render window and allowinteractor between mouse, keyboard and volume dataset within render window which thestep same as method 1. Then, reader created to read the 2D images as volume. Function 'vtkJPEGReader' usedto read JPEG files format. The coding and volume dataset of reader declared same as surface rendering.
Filter used to smoothen and enhance the performance of images. Next, function 'vtkPolyDataNormal' applied to filter the data to build a smooth and clear surface of structure during rendering process. The set value for skin is 500 while for bone is 1150. Then, coding pipeline for filtering skin and bone structure continued with same coding used during surface rendering (method 1) until function 'vtkOutlineFilter'.

Then, the pipeline continues with creating orthogonal planes which passing through volume dataset such as sagittal plane, coronal plane and axial plane. Each plane has different texture map. Color of each plane was set up differently to ease user in observingthe result. Table range set as 2000 to build large table scale. First, black and white lookup(bwLut) table generated. Next, single hue lookup table with a range in the saturation of hue (satLut) created.
After that, first plane which is sagittal plane built. Sagittal plane divides brain into leftand right parts. Filter added to determine the color of the plane. The data map through the lookup table created above by using function 'vtkImageMapToColor'. Thus, the color ofsagittal plane is black. Then, actor display image on single quadrilateral plane using texture mapping which fastening the rendering process. Display extent pipeline and function 'vtkImageMapToColor' only process a slice of data as the display extent value has specified.

Next, second plane which is axial plane and third plane which is coronal plane createdusing the same approach. Axial plane divides above and below part of brain while coronalplane divides front and back of brain. Display extent value set to place the plane at the specific position in the image. Same as method 1 approach used to position camera and added actor to therenderer. Last, solution of the VTK program will be configured or build to create visual studio project files. Then, the file will be debugged to view the result.

3.2.3 Method 3: Volume rendering

Same as method 1 and 2, the first code is to create a renderer with function 'vtkRenderer'. Then, the renderer portrayed into the render window with function 'vtkRenderWindow'. After that interaction between mouse, keyboard and data of the structure within the window was allowed by using function 'vtkRenderWindowInteractor'. Function 'vtkJPEGReader' used as reader to read a set of 2D brain tumor CT images as volume. The data used is same with method 1 and 2.

Ray-cast alpha composes technique applied to display volume. The technique used ray-cast mapper for ray-casting and compositing function to composite along the ray. Voxel color intensities defined by using 'vtkColorTransferFunction' which the function is to map voxel intensities to colors. The color value is specific for targeted anatomy such as flesh and bones. Ideal value of flesh and bone are 500 and 1150. However, RAM PC play important role to run the values. Since it requires high RAM PCto run the values, the value set lower than the ideal value. The most suitable value identified by entering random values below the ideal values.

Next, scalar opacity and gradient opacity adjusted using function ‘vtkPiecewiseFunction’. The scalar opacity identified opacity value at boundaries between tissue opacity which the value is between 0.0 to 1.0, 0.0 is transparent and 1.0 isopaque. Gradient opacity is opacity value at ‘flat’ regions of volume without disturbing the opacity at boundaries between tissue types. The ranges are between 0.0 to 1.0 which 0 is transparent and 1.0 is completely opaque. Function ‘vtkVolumeProperty’ used to define color and opacity to volume and to setsother volume properties such as lighting and shading. Linear interpolation plays importantrole in performing high quality rendering. Function ‘ShadeOn’ is to improve directional lighting that shall enhance the performance of the volume and give ‘3D’ view. On top ofthat, the shading depends on gradient of volume that able to be defined while noisy valuecausing weak gradient estimation. Thus, impact of shading improved by improving the gradient which the gradient enhanced by lowering ambient coefficient, increasing the diffuse and specular coefficient.

Function ‘vtkVolume’ act as ‘vtkActor’. It controls the position and orientation of the3D structure in world coordinates. Lastly, volume added to the renderer. The initial view of the volume set up which thefocal point should be the center and the camera position should be 400 to the left side ofpatient. After that, size values of the render window increased and interact with the data. Last, solution of the VTK program will be configured or build to create visual studio project files. Then, the file will be debugged to view the result.

3.2.4 Method 4: Volume rendering with measuring features

This method allow user to measure length between two points, identify coordinates and size of pixels. The pipeline starts with function ‘vtkPlane’ to update and clip the object in the scene. Next, interactors features and commands for interaction between mouse, keyboard andthe scene added to the program.

The file format used in this method is JPEG. Thus, the size of one pixel cannot be determined. In order to measure the length between two points, pixel length assigned to 0.26458 mm because 1 pixel equal to 0.26458 mm. The value assigned to estimate the pixel size of the image. Next, set of 2D images as input data read by reader as volume by using function‘vtkJPEGReader’. Next, function ‘vtkImageShiftScale’ used for shifting pixels, then scaled. After that output scalar set up similar to ‘vtkImageCast’ as shift scale usually convert data types. Next, filter added using function ‘vtkPieceWwiseFunction’ to enhance the quality of images. Opacity set at certain value (pixels value , opacity value). Then, color of the volume set by using RGB color mode range (pixels value, value of R, G, B).

Properties of volume rendering represent by using function ‘vtkVolumeProperty’. Ambient value to define surrounding of organ structure which is darker or brighter. The lower value produce darker surrounding and vice versa. Set diffuse value determine the diffuse lighting coefficient. Set specular value define lighting in the render window whichhigher value result in brighter value. Set specular power gives mirror effect which highervalue result in darker image with higher contrast.

Next, coding continued with function ‘vtkVolumeRayCastCompositeFunction’ to allow rendering process for formation of 3D image. Then, function ‘vtkPlane’ applied to add plane for cross-sectional view of the brain. Outline filter build for creating a box that place the 3D rendered image.

Then, two sphere with radius 10 mm act as a two point in the rendering window added by inserting function ‘vtkSphereSource’. The color of the sphere determine by adding value at diffuse color using RGB value. The value of R, G, B set as 1, 0, 0 result in red sphere. Next, a line created after two points generated. The resolution of the line set as 200and the diffuse color of the line set as green using RGB color range mode.

After that, cell picker created to shoot a ray into volume scene, hit the object in the scene and return the information of the object such as coordinates and dataset that was picked. Mapper and actor play important role in displaying the result of picking. Hence, thecoding continued with text mapper and actor.

Next, function ‘vtkInteractorStyleTrackballCamera created to allow interaction betweenmouse, keyboard and the scene camera such as zoom in and zoom out. Background color of renderer window set up by using RGB color range mode. Next, the solution of the program configured and visual studio files created. The file debugged to view the 3D model. Then, two reference points and line between the points created. Last, length of the line popped up and result recorded.

3.3 3D reconstruction methods using 3D slicer software

3.3.1 Method 1: Display surface 3D model

3D slicer software installed and run in the computer. The application opened and several features that will be used for 3D reconstruction appeared.

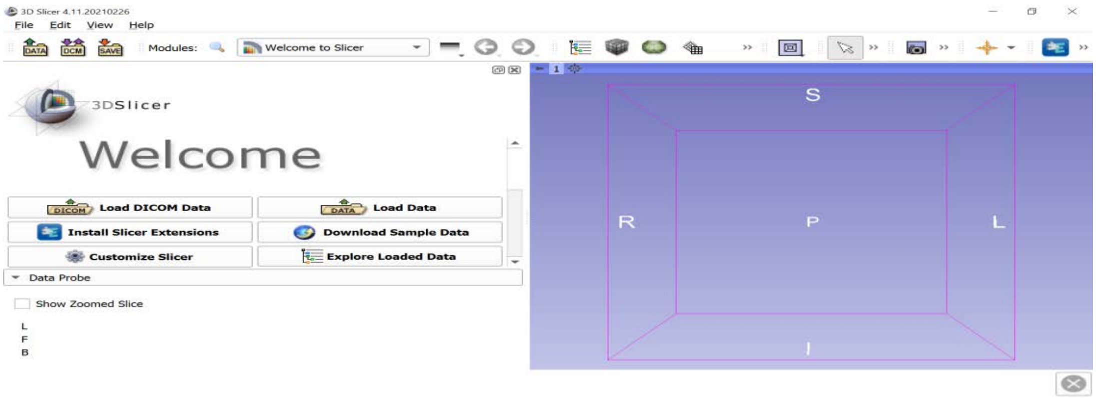

Figure 23: First page of 3D slicer application

Same set of 2D brain tumor CT images used as input data for 3D reconstruction using 3D slicer software. There are 26 slices of images that will be reconstructed into 3D images. The images arranged in an orderly manner and saved in one folder named as 'Imaging image' folder. Resolution of the images are 1012 X 706. The file format is Joint Photographic Expert Groups (JPEG) format.

One of the widgets called as 'add data' widget allow user to add dataset into the scene. The widget clicked and directory folder chose to add into the scene. Then, the folder selected and button 'okay' clicked to confirm the choice that will be added into the scene.

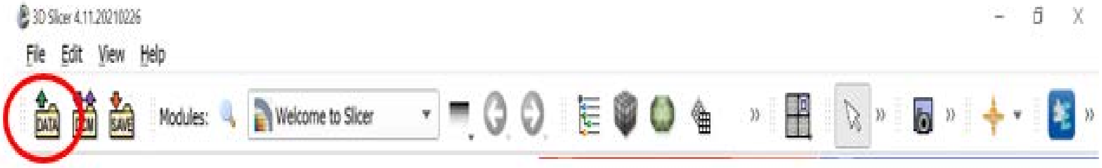

Figure 24: The red circle shows 'add data' widget

Figure 25: The red circle shows button to choose directory folder.

Then, the scene set as 'four up' scene which allow user to visualize scene in four views which are axial view, coronal view, sagittal view and volume view.

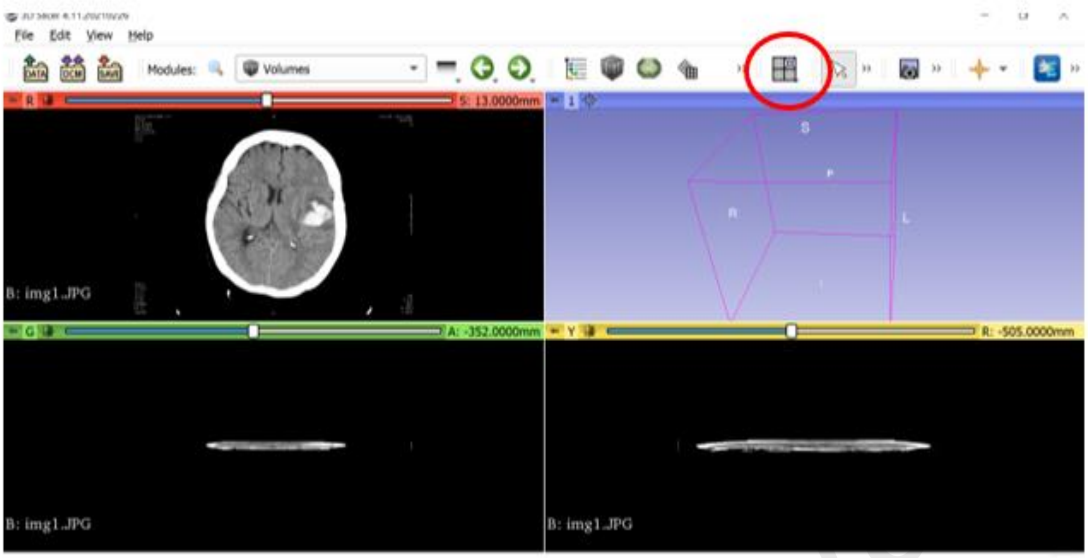

Figure 26: Red circle shows scene widget set as 'four up' scene. Red coloured tab shows axial view, green coloured tab shows coronal view, yellow coloured tab shows sagittal view and blue coloured tab shows volume view.

After that, volume module selected to set suitable value for image dimension, image spacing and image origin. Image dimension set up based on images resolution (1012 x 706) and number of slices used for the scene (26 slices). Optimum value for image spacing for the folder set up in the scene using 3D slicer software same as image spacing value used in VTK which is 1mm x 1mm x 20mm.

Figure 27: Red circle shows volume modules widget that used to modify volume information

Next, volume rendering module selected. Volume view allowed by selecting 'open eye' symbol. Then, the property set as CT-bones pre-set for 3D model display and the scene set as view to all mode to include all images in the selected folder for 3D reconstruction. Last, scalar opacity and gradient opacity adjusted by modifying the 'shift' level in order to view surface of 3D model in the scene. The result of 3D model in the scene observed and compared with result of surface rendering using VTK.

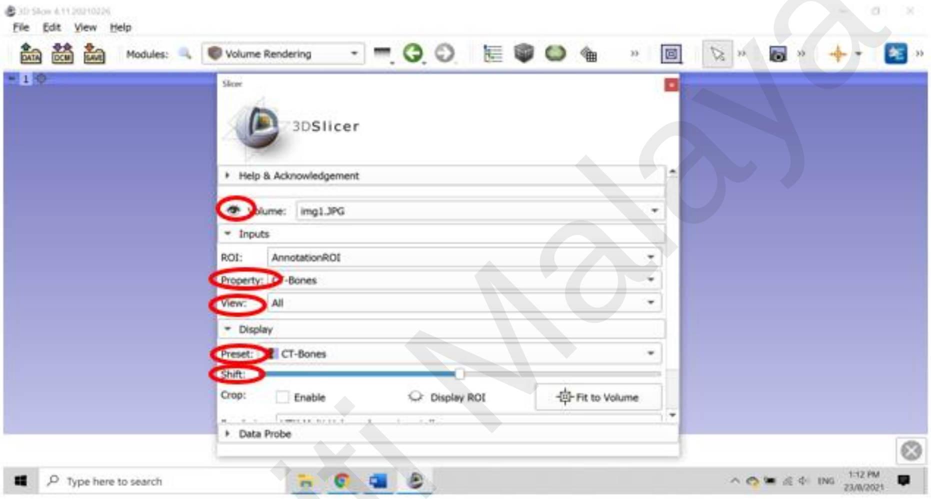

Figure 28: a) The red circle shows eye symbol to allow 3D model to display on the scene. b) the red circle shows property of the volume scene. c) The red circle shows view mode for the scene. d) The red circle shows type of pre-set selected for 3D model display in the scene. e) The red circle shows the shift level for the 3D model.

Next, 'human' widget clicked to allow user visualize direction view of 3D model.

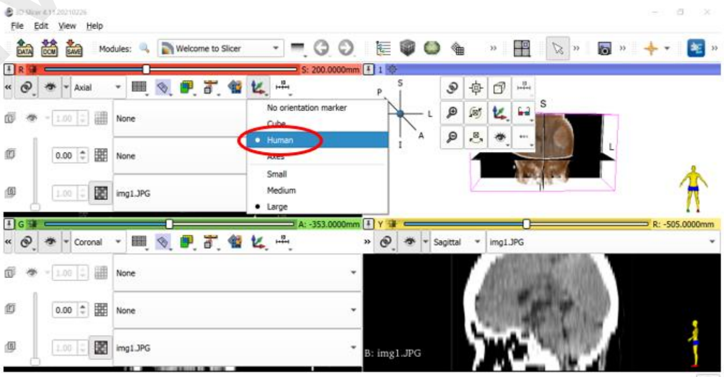

Figure 29: The red circle shows human widget that will allow user view direction view of 3D model.

3.3.2 Method 2: Display multiplanar 3D model

Method 1 repeated. Next, the ‘shift’ level reduced to allow user visualize the brain tumor in multiplanar 3D model. Next, ‘open eye’ symbol in axial view, coronal view and sagittal view clicked to view axial plane, coronal plane and sagittal plane on volume scene. Then, the plane position adjusted to allow user visualize the brain tumor in 3D model. Last, the result compared with result of multiplanar rendering using VTK.

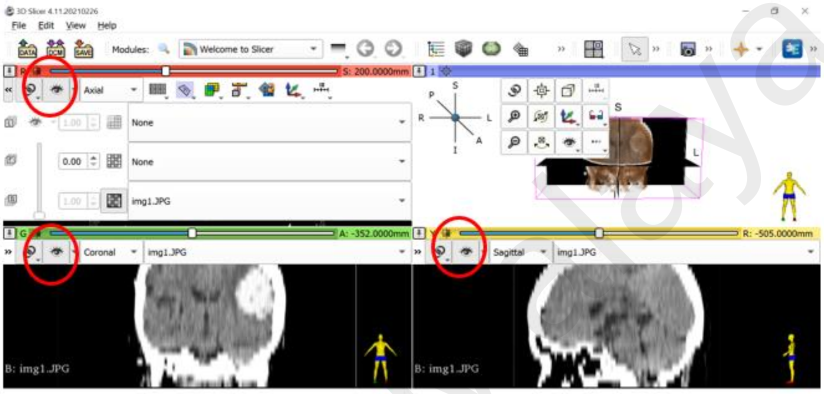

Figure 30: The red circle shows 'open eye' symbol that need to be clicked in order to visualize multiplanar plane.

3.3.3 Method 3: Display volume 3D model

Method 1 repeated. Next, editor module clicked and the images used for this step selected. Next, three structure layers that will be used for creating volume of the 3D model added into the scene. The layers labelled as bone, central nervous system and tissue structure.

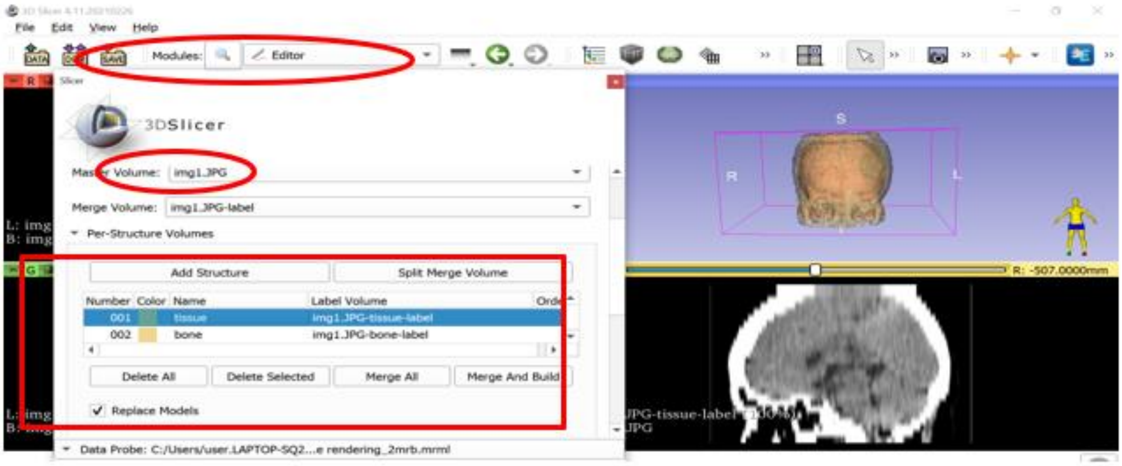

Figure 31: a) The red circle shows type of module selected. b) The red circle shows the image files for editing. c) The red square shows type of structure in each layer.

Next, one of the structure layers chose and 'threshold effect' tool selected to adjust structure area for the layer. Then, 'paint effect' tool selected to select specific structure area for the layer. After that, color of each layers chose where tissue layer is green, bone layer is cream color and central nervous system layer is yellow.

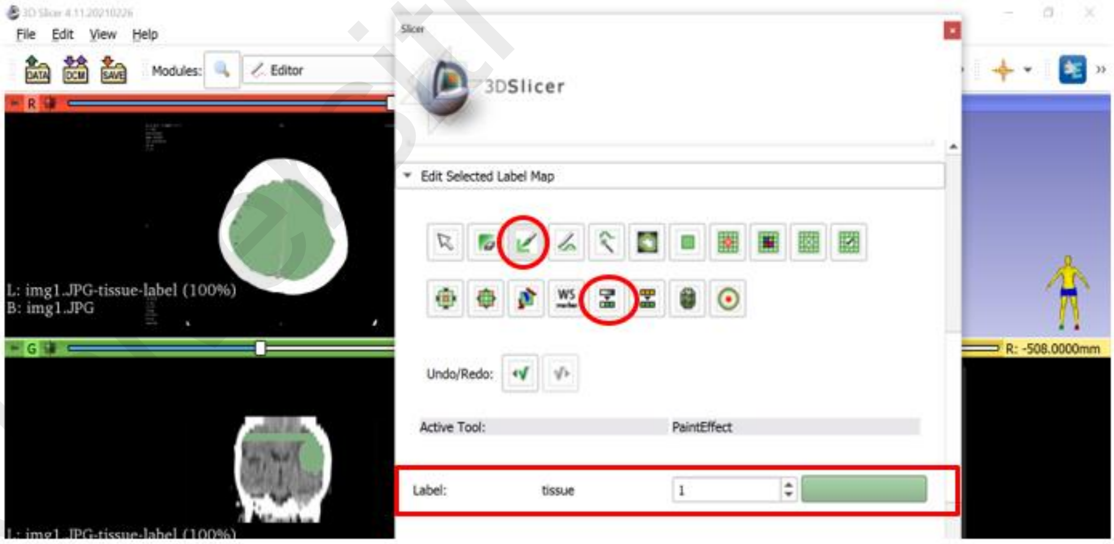

Figure 32: a) The red circle shows paint effect tool. b) The red circle shows threshold effect tool. The red square box shows label and colour of the layer.

Next, model maker module selected to build the layers into 3D model. Then, the input volume which obtained from editor module data selected for 3D reconstruction. Then, apply button clicked to debug the folder.

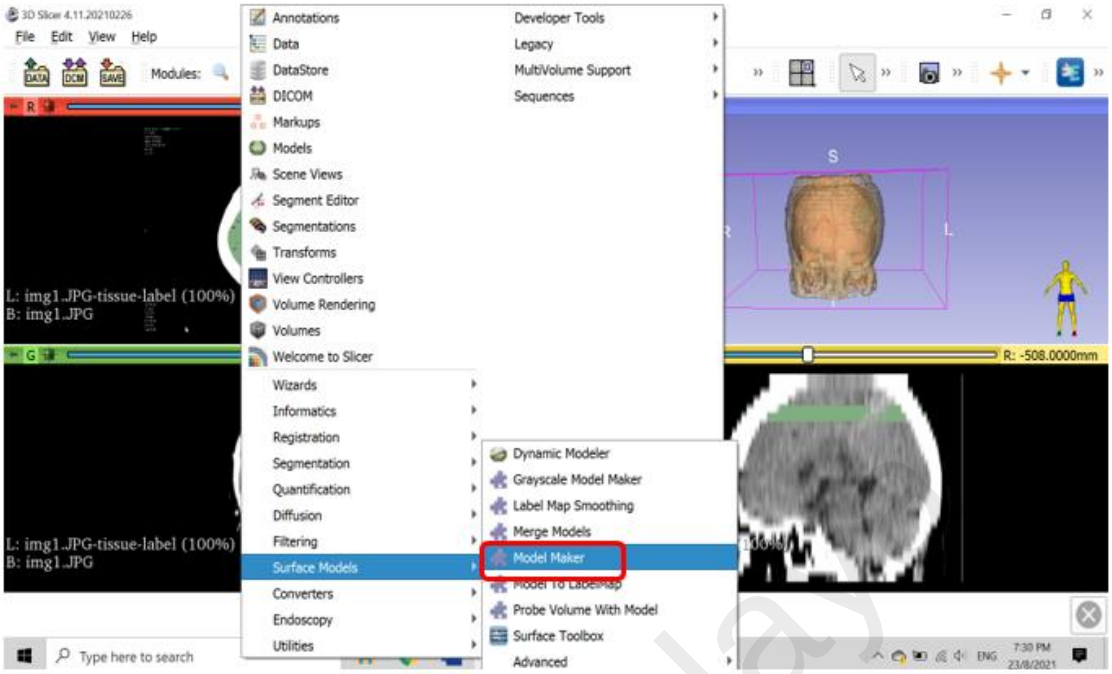

Figure 33: the red square box shows model maker module

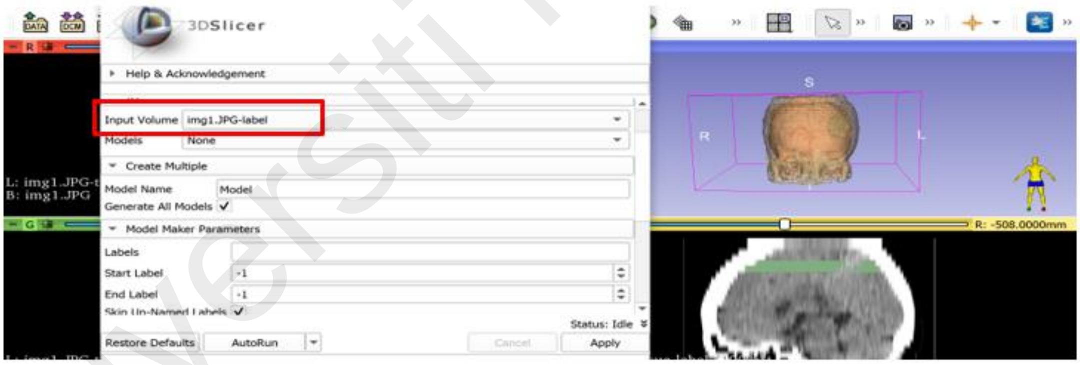

Figure 34: The red square shows input volume data selected

Next, model module selected to adjust opacity level in each layer. Layer selected and opacity level adjusted to optimum level for observation. Last, the result compared with result of volume rendering by using VTK.

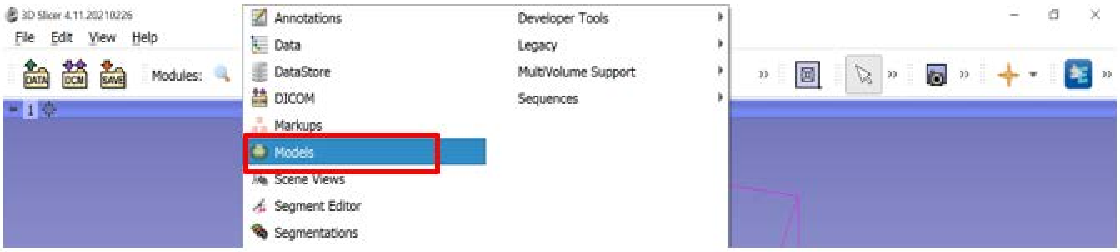

Figure 35: The red square shows model modules.

3.3.4 Method 4: Display volume with measurement of 3D model

Method 3 repeated. Then, fiducial tool used to create reference point. The reference point positioned on brain tumor image from highest point to lowest point (y-axis) of brain tumor and left point to right point (x-axis) of brain tumor. Next, ruler tool used to measure the length between reference point in each axis. Last, the result compared with result of volume rendering with additional features by using VTK.

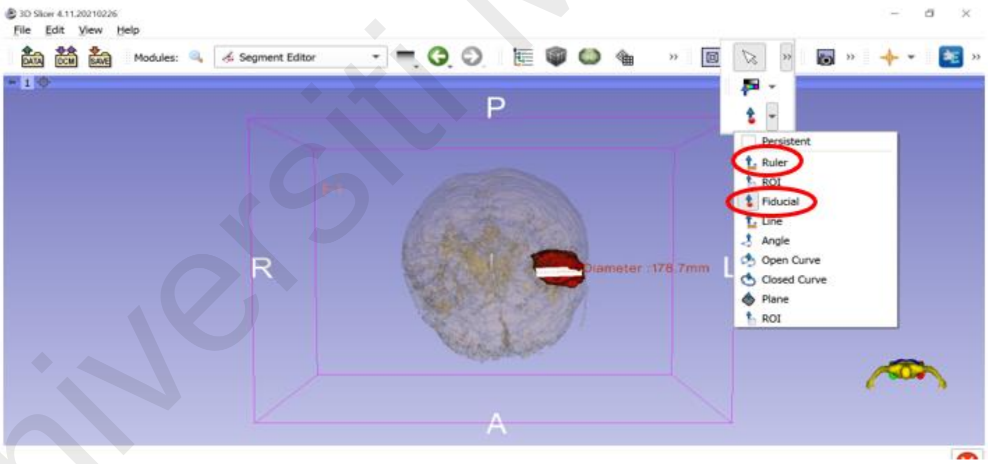

Figure 36: a) The red circle shows fiducial tool to create reference point. b) The red circle shows ruler tool to measure length between two reference points

CHAPTER 4: RESULT

4.1 Surface rendering technique by using VTK software

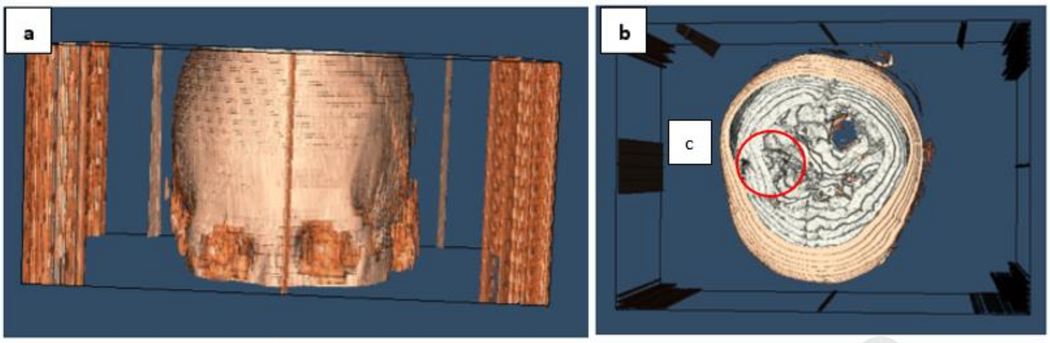

Figure 37: Result of surface rendering by using VTK, a) front view, b) top view and c) the red circle shows the position of brain tumor.

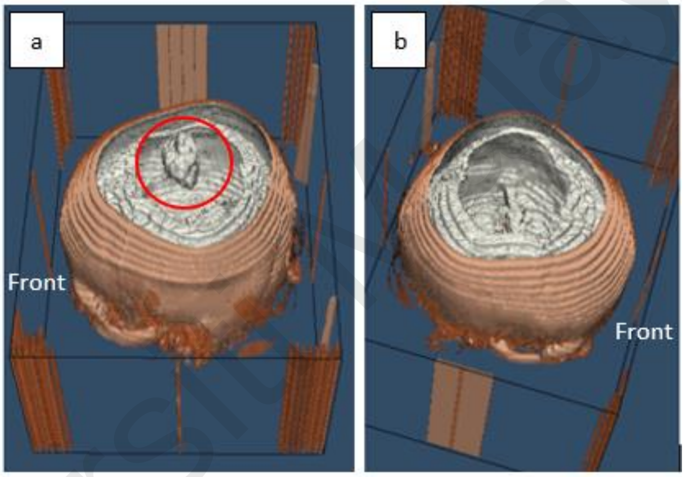

Figure 38: Result of surface rendering by using VTK, a) top-right side view shows brain tumor in the red circle and b) top-left side view shows no brain tumor available.

Result of surface rendering technique by using VTK shows entire 3D model as seen in the head. It shows location of the targeted tissue which is brain tumor. However, the brain tumor cannot be seen clearly as the structure hidden behind an overlying bone and crowded inside of the head with artifacts.

4.2 Multiplanar rendering by using VTK

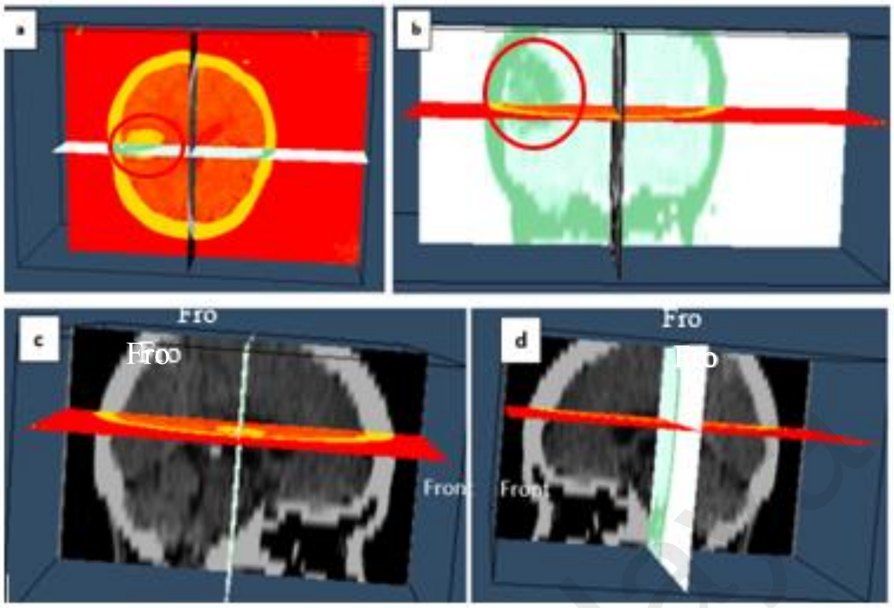

Figure 39: Result of multiplanar rendering, a) top view shows axial plane with brain tumor as shown in the red circle, b) front view shows coronal plane with brain tumor as shown in the red circle, c) right side view and d) left side view shows sagittal plane.

Result of multiplanar rendering technique by using VTK shows axial, coronal and sagittal plane where the axial plane is red color, coronal plane is white color and sagittal plane is black color. All the planes called as orthogonal planes. As shown in the diagram above, axial plane divides below and above part of brain, coronal plane divides front and back part of the brain and sagittal plane divides left and right part of the brain. The result allow user view the location of brain tumor through three orthogonal planes.

4.3 Volume rendering by using VTK

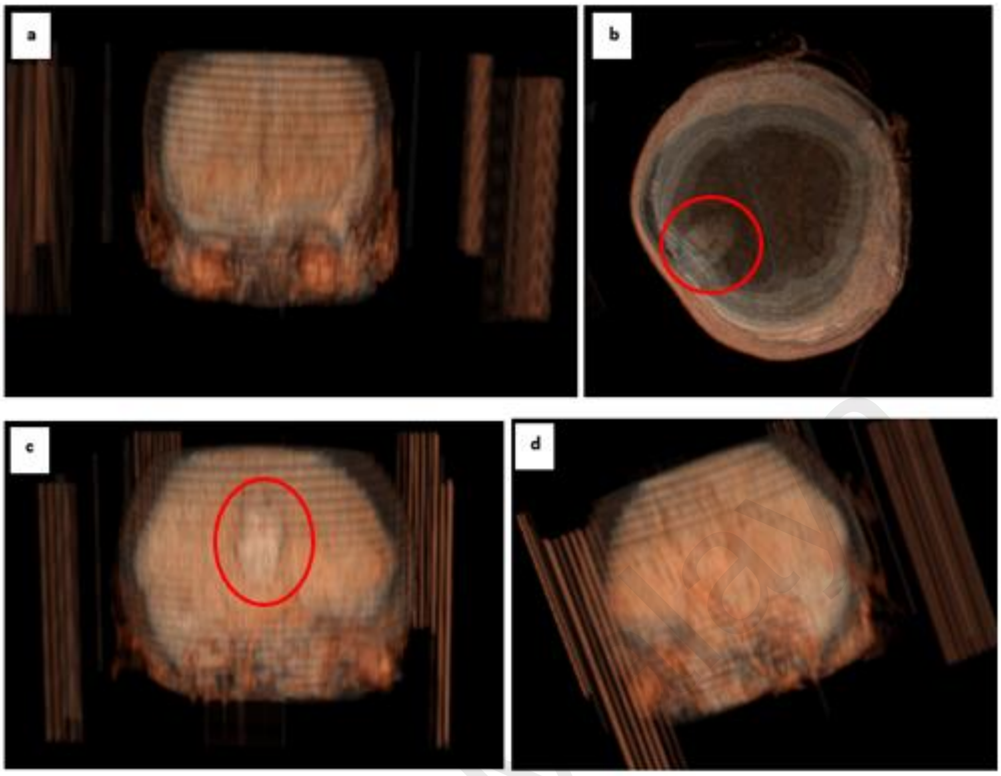

Figure 40: Volume rendering technique by using VTK, a) front view, b) top view shows brain tumor in the red circle, c) right side view shows brain tumor in the red circle and d) left side view

Figure above shows 3D model of brain tumor inside head from different angle view. The result shows region of interest with few artifacts, tissues and bone structure. This technique plays with shading and opacity level to increase image qualities and allow user to visualize region of interest. The shading and opacity that was set during volume rendering make the brain image looks real 3D and the quality of the reconstructed 3D image affected.

4.4 Volume rendering with additional features by using VTK

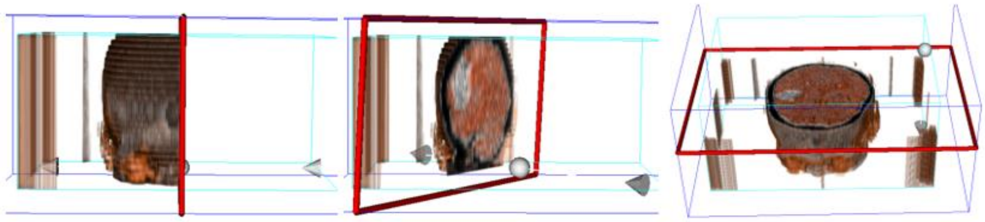

Figure 41: Result of volume rendering with additional features. The diagram shows a red plane with white arrow that allow user to view cross-section of the model.

Result of volume rendering with additional features by using VTK allow user to visualize and crop 3D image and measuring length between two points in the scene. The diagram above shows present of a red plane in the scene. The red plane allowed to move across the head in different position and shift 360° by adjusting the white arrow as shown in the diagram above. Plus, it enables user to crop the image when the plane moves across the structure and view cross-section of the model in the scene as shown in the figure above. Targeted structure to be observed in this research is brain tumor. Thus, user free to view the brain tumor inside of the head according to the inclinations of the plane. This is because of the technique in this rendering method allow user to observe the brain tumor effectively. The result shows tissues, bone and area of interest with few artifacts as cross-section of the model can be visualized.

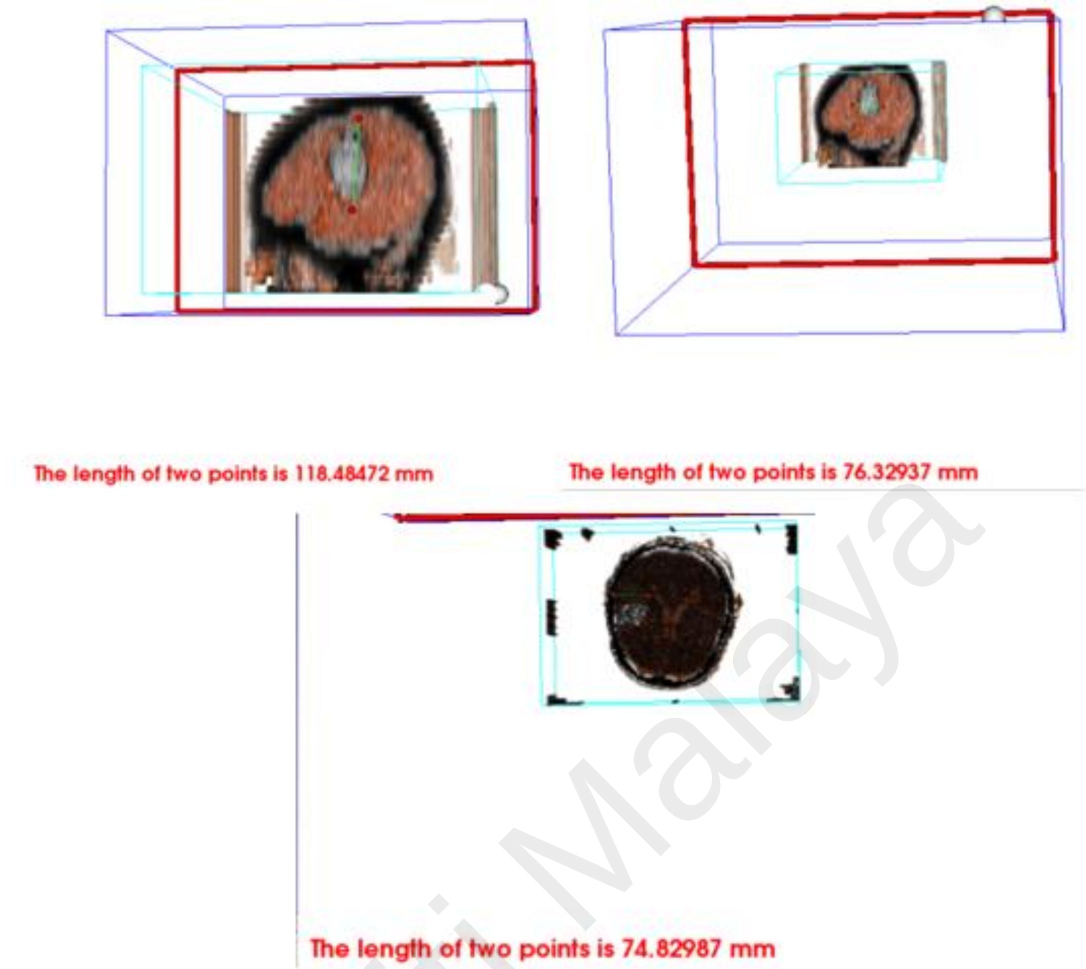

Figure 42: The diagram shows length measurement features

Length between two points measured by using measurement features in the rendering method. This method allows mouse and keyboard interact with the scene. When the mouse is left clicked in the scene, a reference point created. Then, when two points created, the mouse is right clicked and a green straight line between two points appeared and the length shown automatically as diagram above. The diagram above shows that the length between two points in y-axis (first picture) is 118mm, in x-axis (second picture) is 76mm and in z-axis (third picture) is 74mm. Thus, the size of brain tumor in this research identified by using this method is 7.6cm x 11.8cm x 7.4cm.

4.5 Surface of 3D model by using 3D slicer software

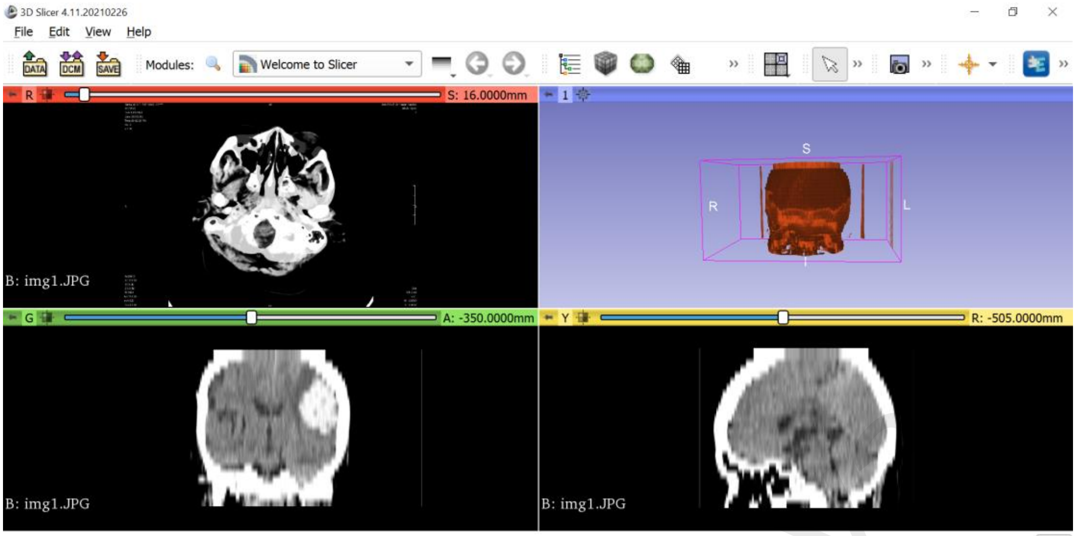

Figure 43: The diagram shows different plane in a single window.

Result of 3D slicer allow user to view four different planes in a single window as shown in the diagram above when the scene set as 'four up' scene. The planes are axial view (red coloured tab), coronal view (green coloured tab), sagittal view (yellow coloured tab) and volume view (blue coloured tab). In addition, 3D slicer result enables user to visualize cross section of the 3D model by moving the slider.

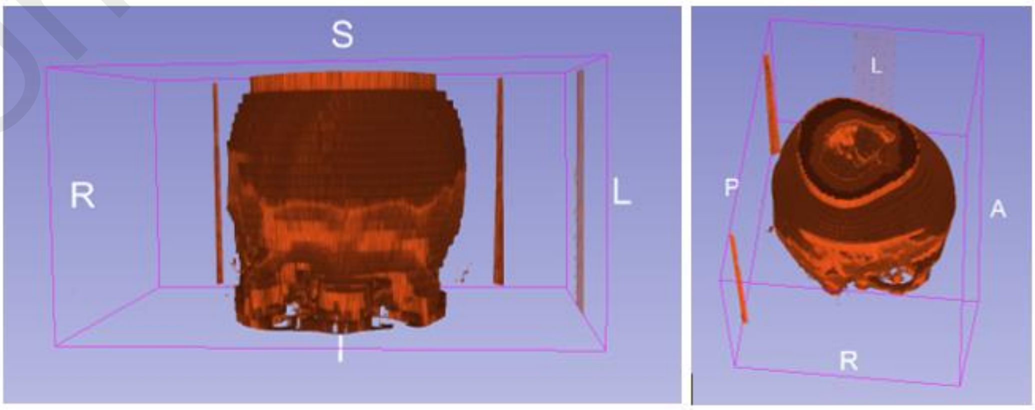

Figure 44: The diagram shows surface of 3D model

Result of this method shows entire 3D model of the head with brown-orange color and structure inside the head. Furthermore, it shows location of targeted tissue inside the head. The targeted tissue is brain tumor. However, the brain tumor cannot be seen clearly as the opacity level of outer surface is high and the targeted structure hidden behind an overlying bone. Plus, there is artifacts inside the head which causing blur view inside the head.

4.6 Multiplanar of 3D model by using 3D slicer software

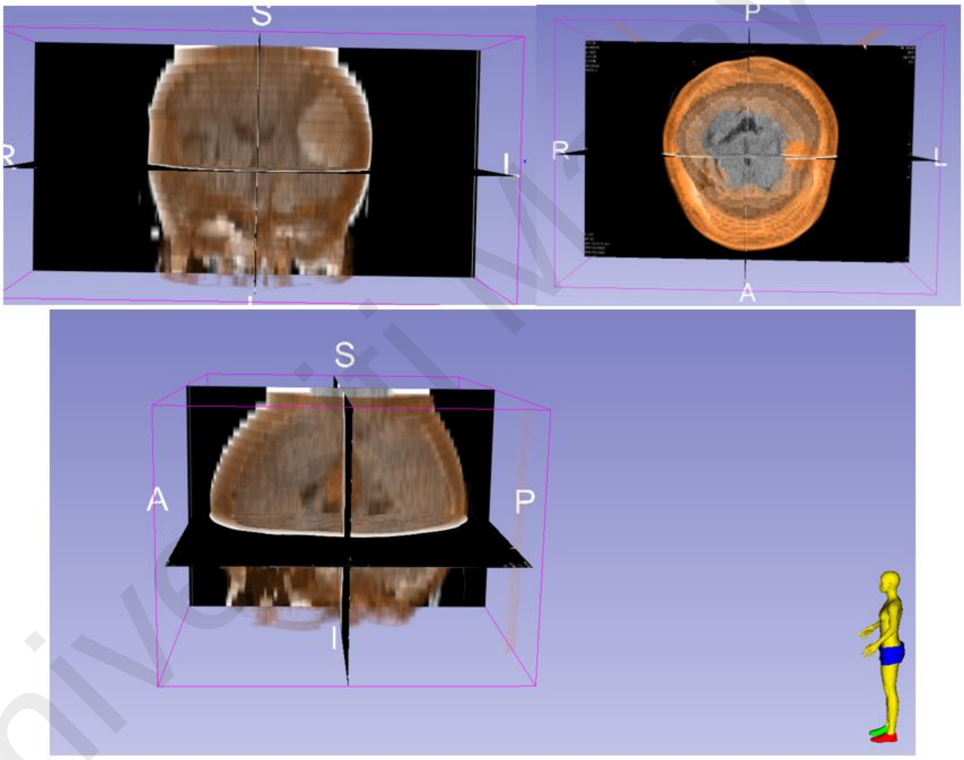

Figure 45: The diagram shows multiplanar of 3D model by using 3D slicer software

The diagram shows three orthogonal planes which are axial plane, sagittal plane and coronal plane created by using 3D slicer software. Axial plane separates below and above part of the brain, coronal plane separates front and back part of the brain and sagittal plane separates left and right part of the brain. All planes are black in color. There is human icon that shows view direction of the 3D model. The first image shows the brain tumor located at the upper-left side of the brain. Second image shows the brain tumor location from top view. However, some of the brain tumor part hidden behind the bone. The third image shows the brain tumor location from left side view.

4.7 Volume of 3D model

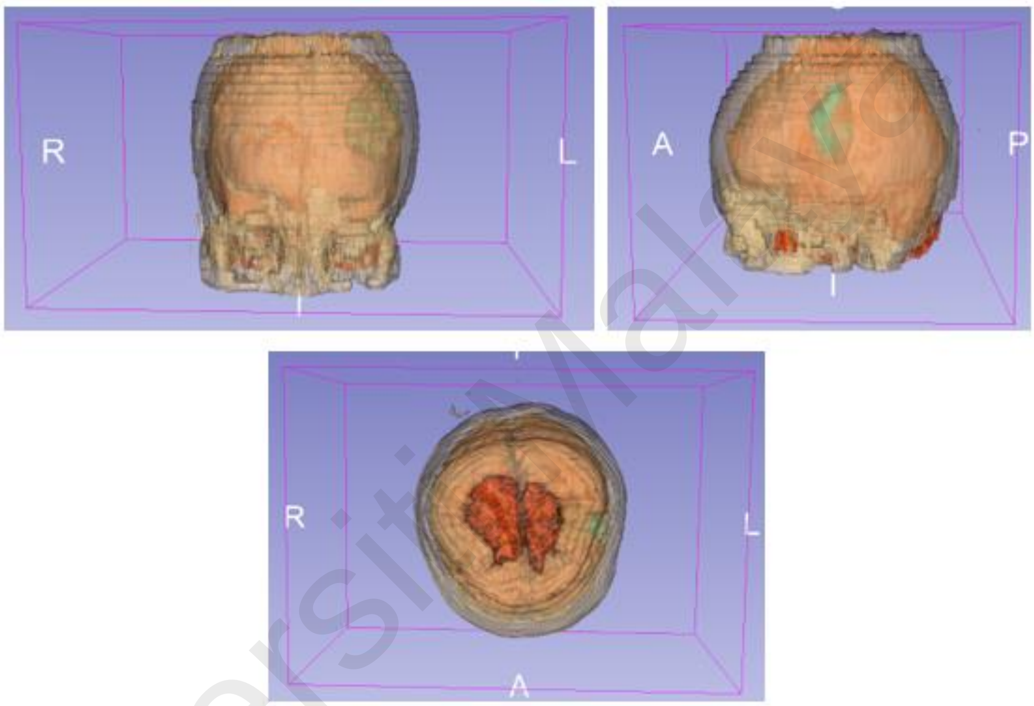

Figure 46: The figure shows volume of 3D model

The diagram above shows volume of 3D model method by using 3D slicer from different angle view. The result shows skin tissue, bone structure and region of interest with few artifacts. The brain designed with bright red color with low opacity level. The region of interest which is brain tumor tissue is easily to be seen as it is opaque and bright green in color. The image looks real 3D due to shading and opacity that was set for the 3D reconstruction.

4.8 Volume with measurement of 3D model

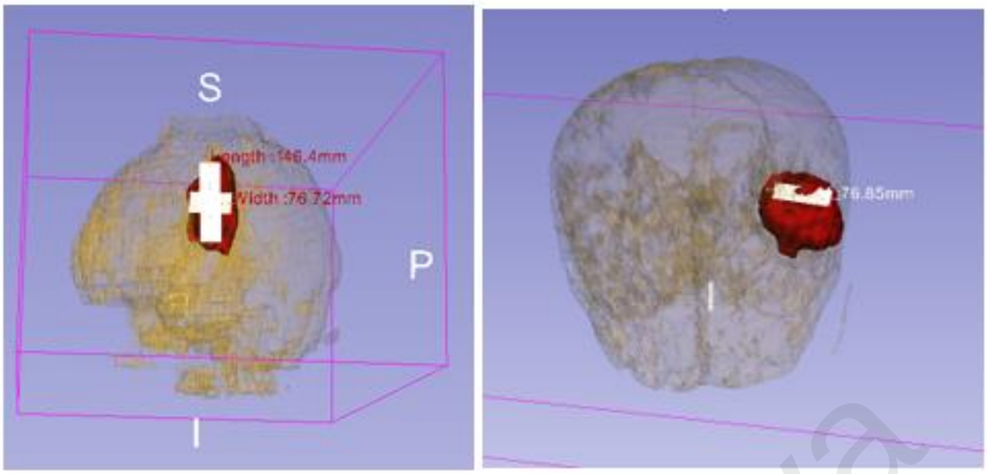

Figure 47: The diagram shows volume with measurement of brain tumor by using 3D slicer software.

Result of this method allow operator to visualize 3D model of brain tumor and measure the size of brain tumor. The diagram above shows that 3D model of brain tumor can be seen clearly as very low artifacts present. Plus, the brain tumor is opaque and bright red in colour while other structure has very low opacity level. User free to view the 3D image of brain tumor inside the head with different angle. In addition, the length between two reference point created to identify the length in x-axis, y-axis and z-axis. The result explained the length between two points in x-axis is 76mm while the length between two points in y-axis is 146mm. Last, the length between two points in z-axis is 77mm. Thus, size of tumor identified by using this method is 7.6cm x 14.6cm and 7.7cm.

4.9 Comparison between VTK and 3D slicer

4.9.1 Accuracy of 3D Brain tumor size

Measurement value obtained by using 3D slicer software used as ground truth values to check the accuracy of measurement value acquired by using VTK software (refer Appendix E). The source images in JPEG format contained resolution and pixel definition. The 3D slicer software read the JPEG images and provide the measurement (1cc/1mm).

Brain tumor size obtained by using 3D slicer software is 7.6cm x 14.6cm and 7.7cm $\pm$ 3cm while brain tumor size measured by using VTK software is 7.6cm x 11.8cm x 7.4cm.

4.9.2 Quality of 3D images

Both software able to reconstruct 2D images into 3D image, measure size of 3D structure and start with adding source in JPEG format. However, there are several differences between VTK software and 3D slicer software. First, VTK required operator to write and read core function in C++ coding pipeline while 3D slicer does not required operator to handle algorithm. In other words, VTK need to edit coding pipeline to add or remove filter and edit structure during 3D reconstruction while 3D slicer software used modules to add, remove or edit layers of 3D structure.

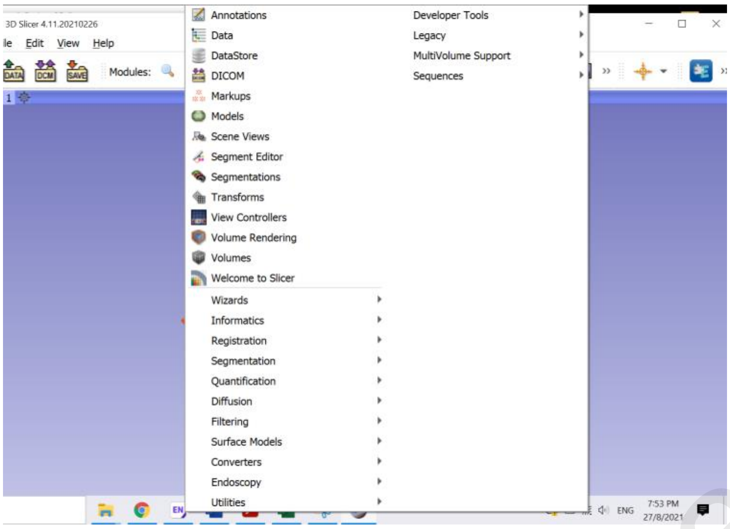

Figure 48: The diagram shows many modules available in 3D slicer software for 3D reconstruction

In addition, 3D slicer allowed user to choose type of window such as many planes in the same window while VTK software is not allowing user to choose type of window.

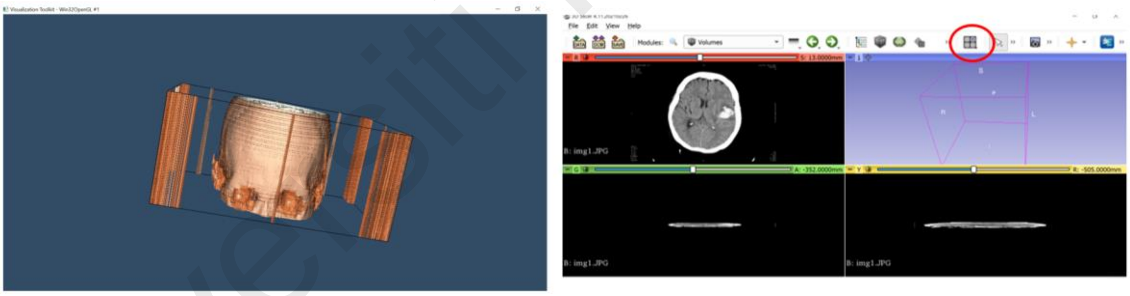

Figure 49: The diagram shows VTK window (left image) and 3D slicer window (right image)

Next, both software allowed user to create orthogonal planes. However, 3D slicer software standardized all planes with black color and not allowed user to change the color of orthogonal planes while VTK software allowed user to change color of planes into different type of color in each plane as shown in the diagram below.

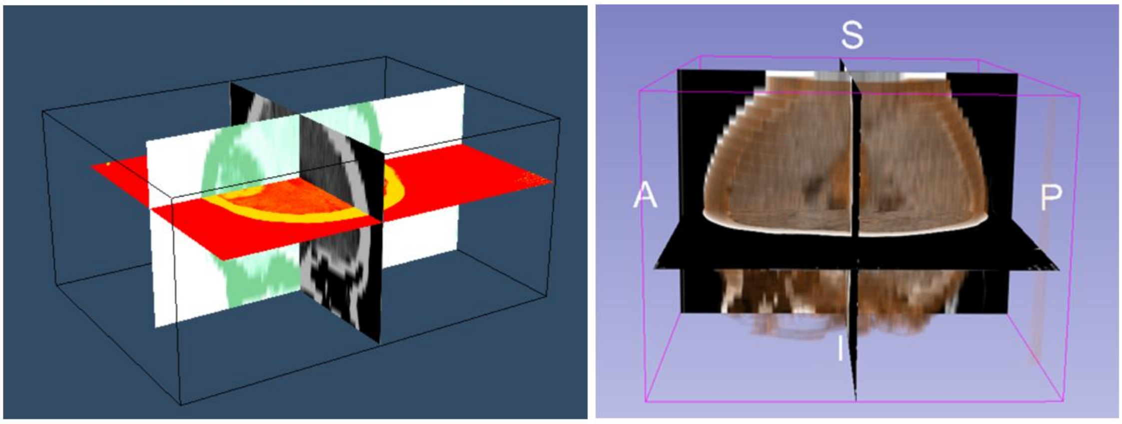

Figure 50: The diagram shows orthogonal planes created by using VTK (left image) and orthogonal planes created by using 3D slicer (right image)

Last, 3D slicer stores data of voxel (origin, spacing and direction) apart in a 4x4 matrix while VTK software used function ‘vtkImageDataOrigin’ and add spacing fields to transform into 3D model.

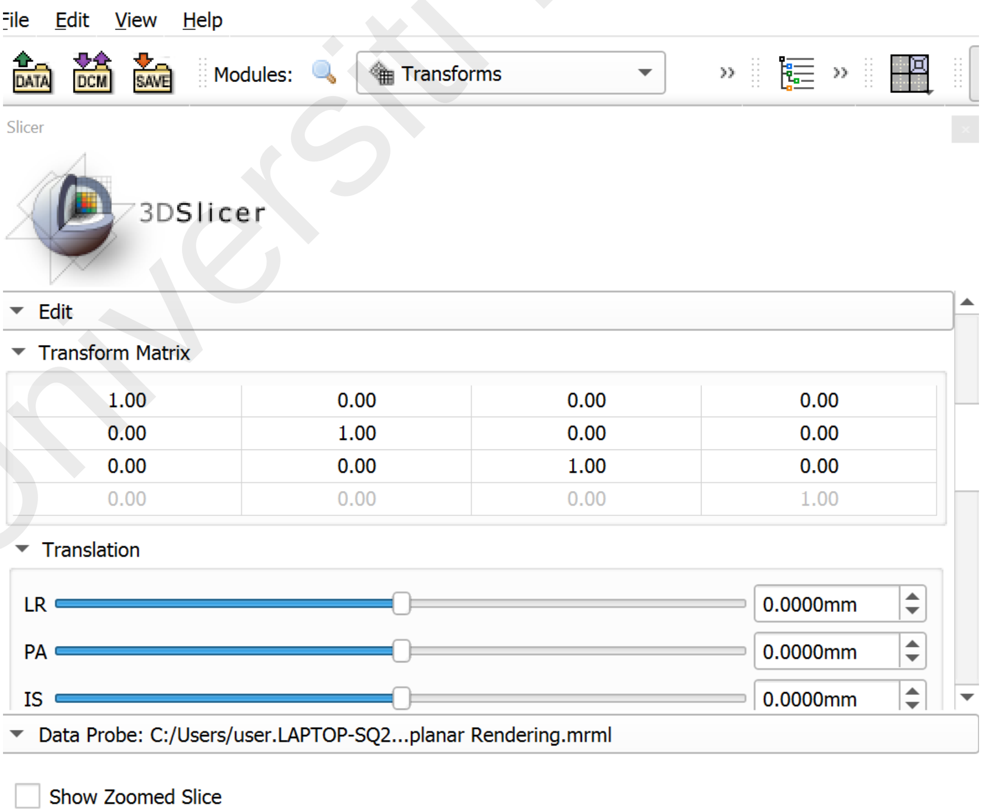

Figure 51: The diagram shows the transform modules in 3D slicer that stores voxel data in 4x4 matrix.

CHAPTER 5: DISCUSSION

There are two important software applied in this research. Each software used 4 different methods for reconstructing and visualizing 3D model of the brain tumor. All methods successfully reconstruct, visualize and measure 3D model of brain tumor as can be seen in result section. However, there are differences in results between each method.

First, surface rendering method by using VTK which is Method 1 shows entire 3D structure of skin and bone surface. However, the brain tumor cannot be seen clearly as there are numerous artifacts inside the head and the method used monotone colored. Thus, operator only able to observe the geometry features of an iso-surface. Major limitation of this method is difficulties in illustrating detail components and structure properties inside the head which located behind skin and bone surface. In addition, shorter time consumed during surface rendering compared to volume rendering causing the quality of 3D image is lower compared to volume rendering method by using VTK (method 3). Numerous artifacts will lowering quality of the image (Boas & Fleischmann, 2012).

In this research, rendering techniques required trials and errors procedure to identify optimum filter value such as value of skin extraction, bone extraction and skin opacity to obtain smooth and clear structure of 3D model. However, the trials and errors procedure based on ideal value. At first, the value of contour value set for skin is 50. However, there are a lot of artifacts present inside the head and the tumor difficult to be seen. Then, the value change to 30. The result shows clearer internal structure compared to previous trial but there are numerous artifacts inside the head and causing difficulties in observing detail structure of brain tumor inside the head. Next, the value of skin extraction lowered to 20, 10 and 5. The result shows that value 20 created lower artifacts, noise and clearer internal and external structure of the surface compared to result of skin extraction value 30, 10 and 5. Even though, structure condition inside the head for value 5, 10 and 20 are the same but their external skin structure is different. The external structure for value 10 and 5 is uneven compared to value 20 due to noise as shown in the diagram below. Thus, the optimum value for skin extraction in this research is 20.

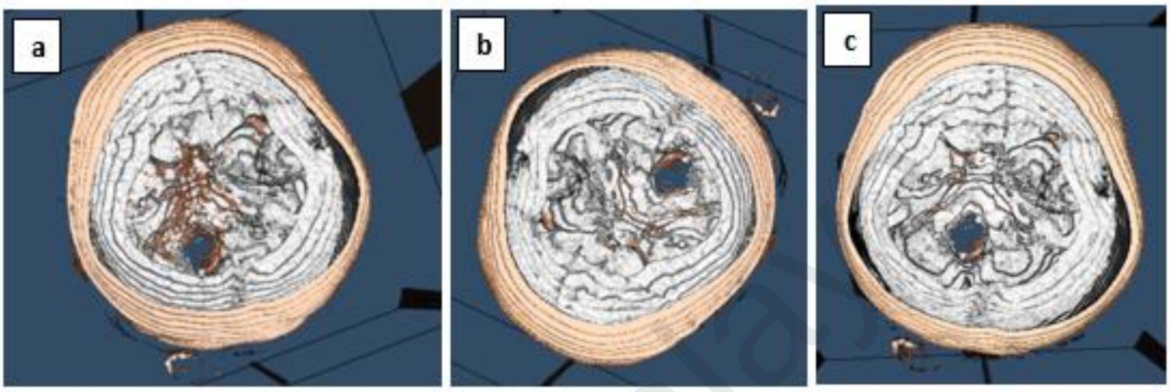

Figure 52: The diagram shows different value of skin extraction. a) The skin extraction value is 50. b) The skin extraction value is 30 and c) The skin extraction value is 20.

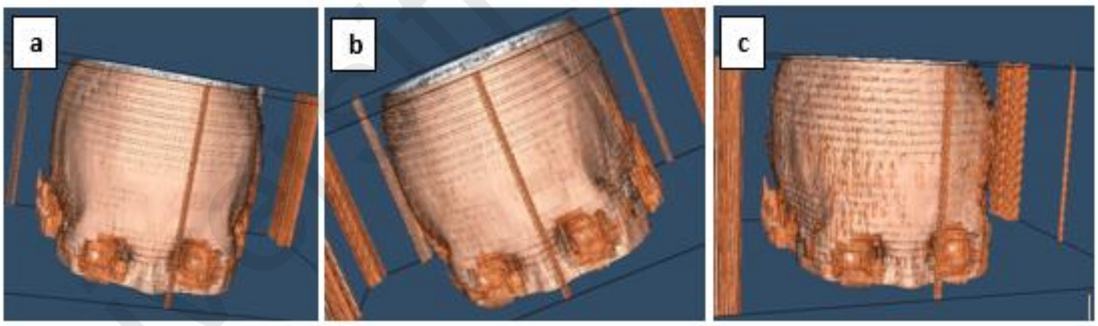

Figure 53: The diagram shows different value of skin extraction result. A) The skin extraction value is 20 shows smooth external surface. b) The skin extraction is 10 and c) the skin extraction is 5 have rougher external surface.

Next, trials and errors procedure continued to identified optimum value for bone extraction. At the beginning, the bone extraction value set as 300. However, the value cannot be read and causing unseen bone inside the head as shown in the diagram below. Then, the value set to 100. The bone inside of the head can be seen but numerous artifacts and noise present causing unclear and rough structure of bone inside of the head as shown in the diagram below. Thus, the optimum value for bone structure set as 200 as the result shows lower artifacts and noise inside of the head compared to value set as 100.

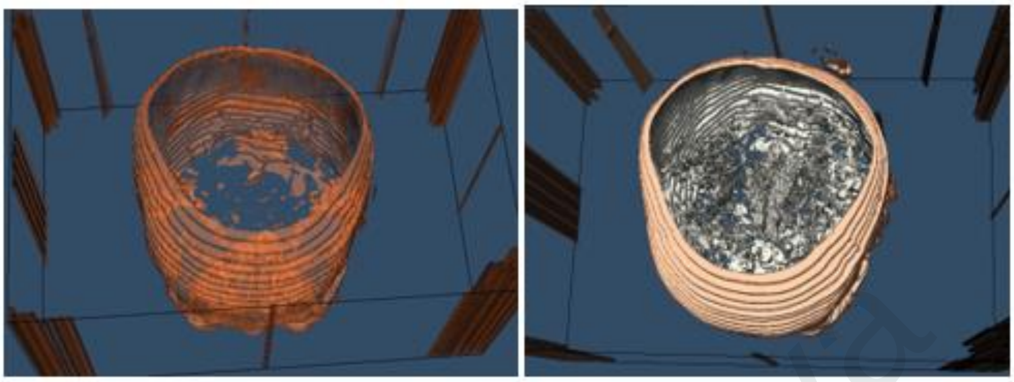

Figure 54: The diagram shows different value of bone extraction result. a) The bone extraction is 300 shows unseen bone inside of the head while b) the bone extraction value 100 shows numerous artifacts inside of the head and unclear bone structure.

Second, multiplanar rendering technique by using VTK which is method 2 shows the relationship between tissue, bone and region of interest in different orthogonal planes such as axial, sagittal and coronal plane. According to Pourtaherian et al. (2017), orthogonal planes help physicians to observe the 3D image. Thus, combination of the planes ease physicians to identify the location of the brain tumor and allow operators to visualized 3D model with orthogonal planes in one scene. However, there is important precaution while running this method. Since, display extent value (x, y and z) used to place specific plane at the specific position. Thus, the minimal value for z in display extent is 1. The program cannot be debugged and the data cannot be recognized if the z-value set as 0 which is less than 1.

Next, volume rendering method managed to reconstruct 3D model of brain tumor successfully but a few artifacts in the 3D image causing the 3D image looks rough and not smooth. Thus, image processing step suggested to be done before conducting this rendering method in order to reduce artifacts in the 3D reconstructed image. The step is selecting region of interest (ROI) to smoothening the model (Tsapatsoulis, Loizou, &

Pattichis, 2007). Plus, image contrasting and shading should be adjusted to increase the intensity of the image and making the image reconstructed sharper.

There are trial and errors practiced in this rendering method in order to obtain optimum value of opacity and enhance shading of 3D image. Optimum opacity value and shading level produce good quality of 3D image and give real 3D looks. On top of that, number of slices play important role in building quality 3D image. Higher quality of rendered image produced when more layers of 2D images used as input data to reconstruct the 3D image. 3D model allows physicians to diagnose disease and plan for further treatment accurately (Shen et al., 2008). This is because 3D image caused less operator-dependent and improve accuracy in diagnosis such as size of tumor.

3D reconstructed image help user to measure the size of ROI such as length, width and depth of the structure. As can be seen in the result section, volume rendering method with additional features by using VTK allow operators to observe cross section of 3D model and measure the length of the brain tumor in x-axis, y-axis and z-axis easily. The lengths help physicians to plan further treatments accurately and faster. However, there are limitations in using VTK software. High resolution of 2D images and high RAM computer needed to run this rendering method and creating 3D model with few artifacts. Lower RAM computer took longer time during build the solution of the program.

3D slicer software manages to meet objectives of this research where it able to reconstruct 2D images into 3D images and measure the size of tumor. In fact, 3D reconstruction and visualization by using this software is easier and faster compared to VTK. There are a lot of features available in this software and the features are friendly user. There are no experiences or knowledges in visualization technique or programming needed to reconstruct 2D images into 3D images by using this software. In addition, most of the features have same function with VTK such as changing opacity level, choosing

ROI, changing structure color and add and remove layers of 3D structures. The volume of 3D model can be seen clearly as user able to choose ROI and change color of structures in each layer. Plus, the opacity level for each layer of structure can be adjusted easily compared to VTK.

However, there are several issues regarding this software. First, 3D slicer software creates numerous artifacts and a lot of noise inside the head during creating iso-surface of 3D model. The artifacts caused difficulties in diagnosis disease (Barrett & Keat, 2004). Second, color of orthogonal planes is standardized, black in color. The color of the planes cannot be change into different colors while VTK free to change the planes color. This issue creates difficulties during observation of 3D model in different planes because same color of planes creates confusion when change angle of view occurred.

Third, even though user allowed to change opacity level of structure in each layer, cross-section of the 3D image cannot be seen causing difficulties to user in determining accurate location for reference points, creating line between the points and measure the length of the line.

In addition, 3D slicer used different transformation technique compared to VTK. This software stores data of VoxelToObject transform (origin, spacing, direction) apart in a 4x4 matrix while VTK software used ‘vtkImageDataOrigin’ function and spacing fields to transform into 3D model. This causing issue to 3D slicer as not all 2D images are axis-aligned. As a result, the reconstructed 3D image produced flipped. Even though, the 3D model produced by using 3D slicer software is clear, smooth, low artifacts and noise, wrong position of brain tumor could lead to wrong treatment plan.

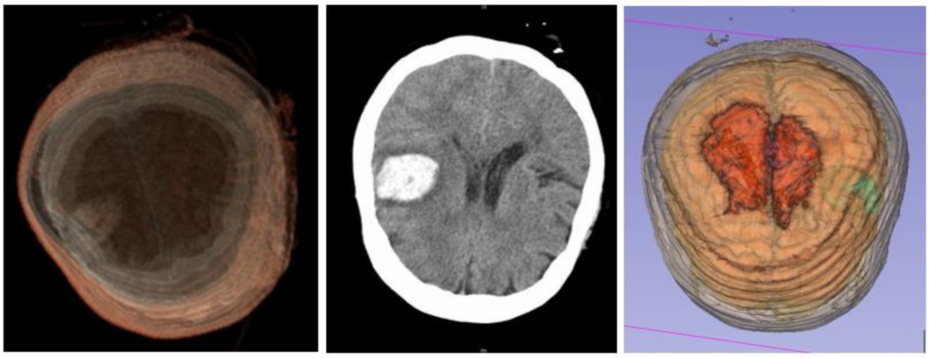

Figure 55: The diagram shows brain tumor position in a) reconstructed 3D image by using VTK, b) 2D CT image. c) The diagram shows reconstructed 3D image by using 3D slicer flipped.

All measurements own degree of uncertainty because of many reasons. Uncertainty allow user to determine the quality of the program as it compared with theoretical prediction. In this research, the size of brain tumor acquired by using VTK is slightly different compared to brain tumor size measured by using 3D slicer. However, the accuracy of VTK software is acceptable as the size of brain tumor obtained is in uncertainty range which is $\pm$ 3cm.

CHAPTER 6: CONCLUSION

In conclusion, this paper shows that both VTK and 3D slicer software capable to reconstruct a set of 2D images into 3D images, visualize reconstructed 3D image and measure the ROI. Objectives of this research achieved. There are eight different methods used in this research to reconstruct 2D images into 3D images and visualized the reconstructed 3D image. Through the research, volume rendering with additional features by using VTK shows the best rendering method to diagnose and visualize a clear 3D model and measure the size of ROI. It has advantages in providing details clearly, observe the inner surface by using crop features and measure brain tumor by using measurement feature. This method could help physicians in planning the best treatment for patient.

Both software show capability in reconstructing and visualizing 3D model of brain tumor. However, VTK rendering method has more flexibility and more precise compared to 3D slicer software. This is because of VTK capability in assigning any values to the volume dataset and enhance the shading and opacity of the 3D model. Plus, it builds 3D model using data origin from source data. Data origin is important in reconstructing correct position of 3D model. Wrong data origin will reconstruct flipped 3D model. Next, VTK software allow user to add and remove filter or edit the structure by adjusting the coding line and dataset value. Since, VTK is open-source software, it can help physicians to reduce time taken in diagnosis and observation of disease as less dependent on human cognitive ability required.

In addition, image processing before volume rendering method should be done in the future to reduce noise and improve quality of 3D reconstructed image. Next, further study on effect of different sets of brain tumor CT images should be done to identify the relationship between number of layers and dimension of images. Plus, the different sets of 2D images can be used to differentiate quality of 3D model produced with different number of slices used for this program. Furthermore, 3D reconstruction software and C++ programming could aid radiologist and physicians in diagnosing and providing treatments to the patients in the future. Plus, the technology is low budget as a lot of open-source software available to reconstruct 3D images from 2D images such as VTK and 3D slicer. Therefore, if the technology embedded into current diagnosis tools, efficient reconstruction images can be practiced with lower budget and healthcare industry able to improve diagnosis quality.

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