UNIVERSITI PUTRA MALAYSIA

SEGMENTING THE RIGHT VENTRICLE CAVITY FROM 4D ECHOCARDIOGRAPHY IMAGES FOR STROKE VOLUME MEASUREMENT

ANAS A. ABBOUD

FSKTM 2014 30

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By

ANAS A. ABBOUD

Thesis Submited to School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of Requirements for the Degree of Doctor of Philosophy

August 2014

Dedicated to my parents, husband, kids, sibilings, and good friends

Abstract of thesis presented to the Senate of University Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

Segmenting the Right Ventricle Cavity from 4D Echocardiography Images for Stroke Volume Measurement

By

ANAS A. ABBOUD

13August 2014

Chairperson: **Rahmita Wirza O.K. Rahmat, PhD**

Faculty: **Computer Science and Information Technology**

Quantitative measurement is an important indicator for assessment, diagnosing and decision making by the specialists. Therefore, Computer Aided (or assisted) Diagnosis systems (CAD) are increasingly affordable; it has been incorporated in routine clinical practice. In this research we address right ventricle (RV) assessment by measuring the stroke volume of the ventricle. This can be done through, segmenting RV cavity, and determining the End-Diastolic (ED) and End- Systolic (ES) stages of the cardiac cycle. Then measure the volume at ED and ES stages to compute the stroke volume. Viewing the whole RV cavity structure is also may give initial assessment for the cavity abnormality.

By reviewing most of the previous work in the literature, there are different methods used to segment the right ventricle (RV) cavity, such as boundary based detection, texture, and regional segmentation methods. All of these methods focused on a manual or semi-automatic extraction of the RV structure. It is obvious that there is a lack of concentration on the multifarious structure of the RV cavity (apex, moderator band, trabecular, and Inflow-Outflow regions). The ED and ES stages for the cavity are

determined manually by review of individual image phases of the cavity, and/or tracking the tricuspid valve. In the other hand, the current 3D reconstruction method of the RV structure is built by original for the left ventricle. Thus it doesn't represent the actual structure of the RV cavity.

New algorithms are needed to assess the abnormality of the right ventricle. This process can be done by accurate segmentation of the cavity, determination of the End-Diastolic and End-Systolic stages of the cardiac cycle, measuring the stroke volume, and reconstructing the three dimension model of the segmented region of the cavity for initial assessment of the abnormality.

In this work, we propose a method for semi-automatic segmentation of the right ventricle to measure the stroke volume from four dimensions (4D) echocardiography, based on a novel analysing for the complex geometrical structure and function of the right ventricle.

The right ventricle structure is simplified by slicing the right ventricle in 4D echocardiography images. Region growing technique is deployed to segment the cavity in each slice. This technique works automatically by detecting a seed point inside the region of interest (ROI), independently utilizing pre-knowledge of the region feature. Then start the iterative region growing segmentation process.Automatic detection for the End-Diastolic and End-Systolic stages of the cardiac cycle is introduced, by tracking the changes area of the segmented region of the cavity along one cardiac cycle. Disk summation principle is used to compute the volume of the segmented region in each slice. The resolution of the xMATREX array TEE transducer (X7-2t) is also estimated to measure the volume in millilitre unit. Then compute the cavity stroke volume by finding difference between the volume of the cavity at the ED and ES stages. The contours of the segmented region are extracted to generate the cloud of points ($\mathbb{R}^3$). Finally, generate three dimensions modelling for the segmented cavity by developing the normal feature approximation method for the cloud point, in order to accurately delineate the required object.

The proposed method requires minimal user-initialization to determine the ROI and executions, which requires only few seconds for one time along the processing time. Comparisons of the segmentation, End-Diastolic and End-Systolic stages, stroke volume and the reconstructed 3D model; are provided with currently available software for left ventricle volume, function assessment and 3D modelling to validate the merit of the proposed work. The results of each step of process are satisfied high acceptance from the cardiologist experts in the qualitative validation, and a good accuracy in quantitative validation regarding to techniques.

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Segmentasi Rongga Ventrikal Kanan dari Imej Ekokardiografi 4D untuk Pengukuran Isipadu Strok

OLEH

ANAS A. ABBOUD

13 Ogos 2014

Pengerusi: **Rahmita Wirza O.K. Rahmat, PhD**

Fakulti: **Sains Komputer dan Teknologi Maklumat**

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Algoritma baru diperlukan untuk menilai keabnormalan daripada ventrikel kanan. Proses ini boleh dilakukan dengan menghasilkan segmentasi rongga yang tepat, penentuan akhir diastolik dan peringkat akhir sistolik kitaran jantung, mengukur isipadu strok, dan membina semula model 3D di rantau rongga yang telah disegmentasi untuk penilaian awal keabnormalan.

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I hereby confirm that:

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CHAPTER 1

INTRODUCTION

This chapter presents a background of the right ventricle anatomy, function, and the echocardiography technique and imaging view, whereby the proposed algorithm of this thesis is based on the anatomical analysis of the right ventricle and echocardiography imaging views. This chapter begins with the motivation that drove the research interest in measuring the right ventricle stroke volume. Next the chapter presents a background of the anatomy and function of the right ventricle, some common right ventricle diseases, and the standard echocardiography imaging views. This is followed by detailed sections of the research problem, research objectives, and the research scope. Finally, this chapter ends with the organization of the thesis.

1.1 Motivation

According to a World Health Organization (WHO) report, Cardiovascular Diseases (CVDs) are the first order of the first ten leading diseases of death in 2011, (WHO. N.p. 2011). This fact is shown in Figure 1.1 and Figure 1.2 respectively. The Malaysian Ministry of Health reported that CVDs were the main cause of death for 23 % to 26 % cases in government hospitals for the period of 1994 to 2001 as stated by Zambahari (2004).

The complexity and criticality of heart disease diagnosis and treatment have frequently attracted the attention of researchers to develop approaches that can handle accurate clinical assessments. One of these complexities is measuring the right ventricle (RV) stroke volume from Three Dimensional Echocardiography (3DE) images. The RV has a particularly complex geometry and accurate stroke volume measurement requires full coverage of the RV cavity. Studies have been undertaken to measure the RV stroke volume, however, these studies were based on geometrical assumptions or intensive manual interaction.

Therefore, different cardiac imaging techniques have been developed to help specialists in their regular clinical work and in the operating theatre to assist in the diagnosis, monitoring of the treatment and to ensure the success of a cardiac intervention as far as possible. Echocardiography is one of the cardiac imaging techniques and is considered as the most effective imaging technique as it is minimally invasive, quick and the cheapest method, Kneeshaw (2006). Real time Three Dimensions Echocardiography (RT3DE) is the most recent innovation of the echo imaging system. This technique provides the potential for improving the image quality and 3D visualization of the entire cardiac chambers, according to Shirali (2008), and Houck et al. (2006).

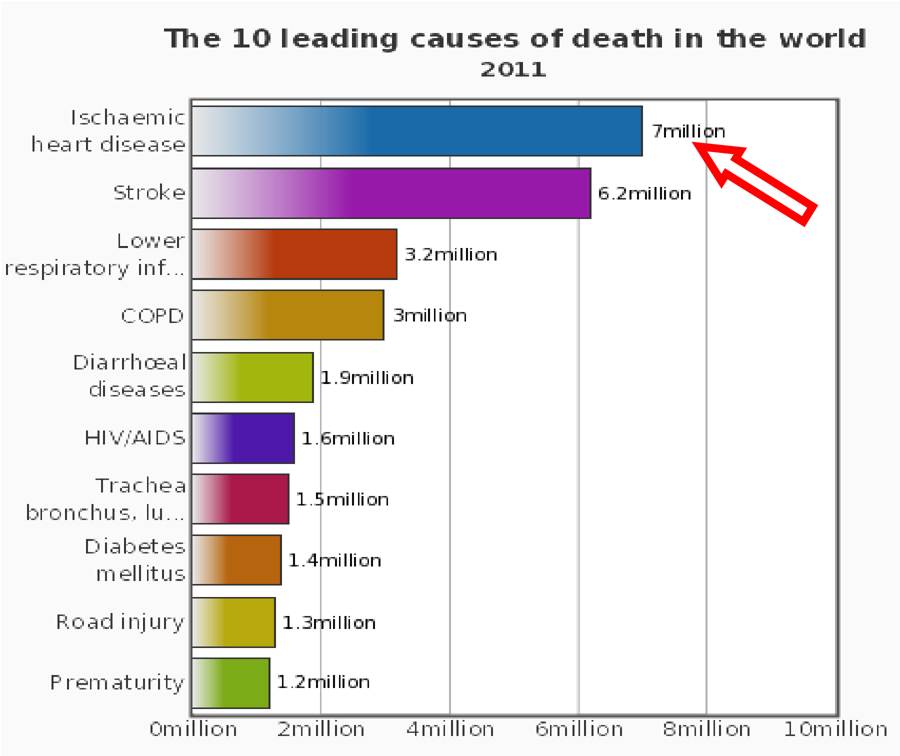

Figure 1.1: WHO report for the 10 leading causes of death in the world in 2011. http://who.int/mediacentre/factsheets/fs310/en/

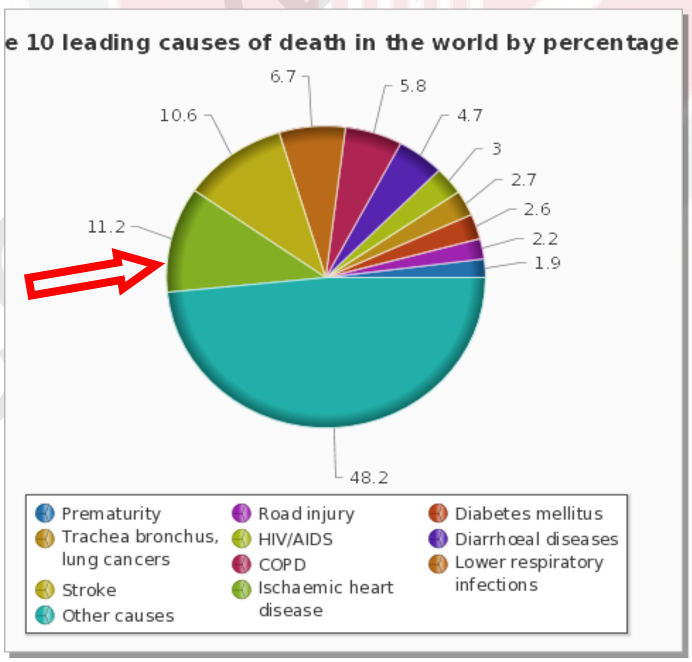

Figure 1.2: Top 10 causes of death in the world for 2011 by percentage http://who.int/mediacentre/factsheets/fs310/en/

Quantitative measurements are an important indicator in any clinical report since they can assist in assessing the normality or abnormality of the structure and function of the ventricles. Therefore, this technique is utilized to provide a numerical measurement as stated by Shirali (2008). Even though the current RT3DE technique succeeds in measuring the left ventricle (LV) function and volume, according to Aune et al. (2009), it cannot provide accurate measurements of the right ventricle (RV) function and volume.

Although many studies have been conducted on RV assessment, this is still a huge challenge for researchers. Most of the previous studies have measured the RV volume using an RT3DE imaging technique by adopting LV measurement methods regardless of the different anatomy between the RV and LV, Gopal et al. (2007), Aune et al. (2009), Crean et al. (2011), and Bell et al. (2013).

The Tom Tec 4D imaging system has been used in some studies to measure the RV volume. This technique presents a volume measurement for the RV based on a 3D model which is built from a manually extracted boundary in three chosen planes. This method requires manual correction and interaction as a part of the work. In addition, the RV trabecular shape cannot be fully covered by only three planes, whereby the direction and number of planes can strongly affect the accuracy of the measurements Hoch et al. (2007).

1.2 Heart Anatomy

This section is detected to give a brief medical background related to the human heart as the subject of this thesis. This section briefly presents the anatomy of the heart, the diseases that may occur in the right ventricle cavity.

The heart consists of four chambers which can be isolated into two sides, namely the left side and the right side. Each side consists of an atrium (atria, or some books may refer to it as atrial) and a ventricle Left Atrial (LA), Left Ventricle (LV), Right Atrial (RA) and Right Ventricle (RV). The atriums receive blood from the body and pump it to the ventricles. The two lower chambers which are called ventricles pump the blood from the heart to all the tissues in the body through a network of blood vessels. In other words, the heart is the least symmetrical organ in the body. The following sections explore the heart anatomy based on the work of Ribeiro (2005) and Bailey (2004).

1.2.1. Right Atrial (RA)

The Right Atrial (or the Right Atrium in some references) is one of the two atriums of the heart. It is situated in the upper part of the right hand side of the heart, attached to the inferior vena cava, superior vena cava and the coronary sinus. It has smooth walls, and is separated from the left atrial (LA) by the internal septum. The function of the RA is to receive the returning deoxygenated blood from the body to the heart through the mitral valve (MV).

1.2.2. Left Atrial (LA)

The LA is simpler than the RA structure. It is located above the LV and receives the oxygenated blood from the lungs through the pulmonary veins, and pumps it to the LV through the mitral valve (MV). More information is available on the website of Iaizzo (2010) and Roy (2009) at *http://www.histopathology-india.net/Atrium.htm.*

1.2.3. Left Ventricle (LV)

The LV is located on the left hand side of the heart and is separated from the RV by the septum and opened to the LA by the MV. Naturally, the LV is larger than the RV because it has thicker walls, and it has a semi-circular geometry on the short axis cross-section and an ellipsoidal shape on the apical (long axis) view as in Figure 1.3 Maffessanti et al. (2009). However, the LV and RV contain equal amounts of blood. The LV receives the oxygenated blood from the lungs through the LA and pumps it to the body through the aorta valve. The process of pumping required high pressure, therefore the wall is naturally thick. The quantity of blood that is pumped from the LV in one cardiac cycle called the left ventricle stroke volume (LVSV).

1.2.4. RV Anatomy

This section is dedicated to explain the RV structure, function and diseases, whereas the core of this thesis is concerned with measuring the stroke volume of the RV.

The RV has a complex and unique geometry. It is located to the right of the LV and it extends from the right atrium to the apex of the heart, wrapping around the LV. The RV is separated from the LV by the septum and it forms a crescent shape, as illustrated in Figure 1.3. The RV structure consists of three regions, namely the Inflow-region for the tricuspid valve, the Middle-region for the apical ‘trabecular’ part, and the outflow region (infundibulum) tract of the pulmonary valve, as in Figure 1.4 based Badano et al. (2010).

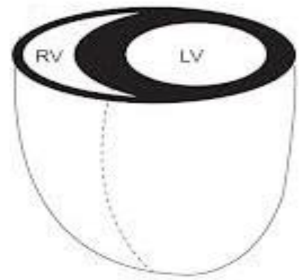

Figure 1.3: Right ventricle and Left ventricle, the short axis plane of the LV is circular, and short axis of the RV gives a crescent shape.
http://www.pulmonarycirculation.org/

The RV receives blood from the body through the RA, and pumps it to the lungs though the pulmonary artery. There the tricuspid valve opens by contracting to the atrium and the pulmonary valve is closed to fill the ventricle with blood. Thus, the process of the RV changes to contraction, the tricuspid valve closes and the pulmonary valve opens to pump the blood to the lungs through the pulmonary artery. The quantity of blood pumped from the RV in one cardiac cycle is called the right ventricle stroke volume (RVSV).

The RV is a strong independent predictor of outcome in a number of distinct cardiopulmonary diseases according to Brittain et al. (2012). Different reasons may cause RV diseases such as pulmonary arterial hypertension (PAH), Blalok et al. (2013).

PAH results from narrowing of the blood vessels for different reasons which causes dilation in the RV structure. The right side of the heart is responsible for pumping the blood to the lungs through the pulmonary arterial vessels. Therefore, in the case of PAH, the right side of the heart needs to work harder in order to pump the blood through these narrow vessels which causes dilation in the RV anatomy over time and as illustrated in Figure 1.5.

Right Ventricle Hypertrophy (RVH) is another disease that may infect the RV and causes a thickening in the RV wall, as in Figure 1.6. This disease occurs in the case of shortening in the pulmonary circulation. The reasons for such shortening are a blockage in the pulmonary valve, a defect in the ventricle septal (right-to-left-shunt), and other genetic or environmental factors.

Another disease that might infect the RV is Arrhythmogenic right ventricular cardiomyopathy/dysplasia (ARVC) or (ARVD). This disease may occur in the RV because of excess exercise, too much caffeine, high blood pressure, coronary artery disease, or it can occur due to a rare disease in the RV muscles. These abnormal muscles may appear in the heart because of genetic effects or different medical conditions and sometimes they can be replaced by fibrous tissues, as illustrated in Figure 1.7. There are different tests that are applicable to diagnose the ARVD disease such as the electrocardiogram (ECG), echocardiography, RV angiography and cardiac MRI, and genetic tests as stated by Basso et al. (2009), Corrado et al. (2000).

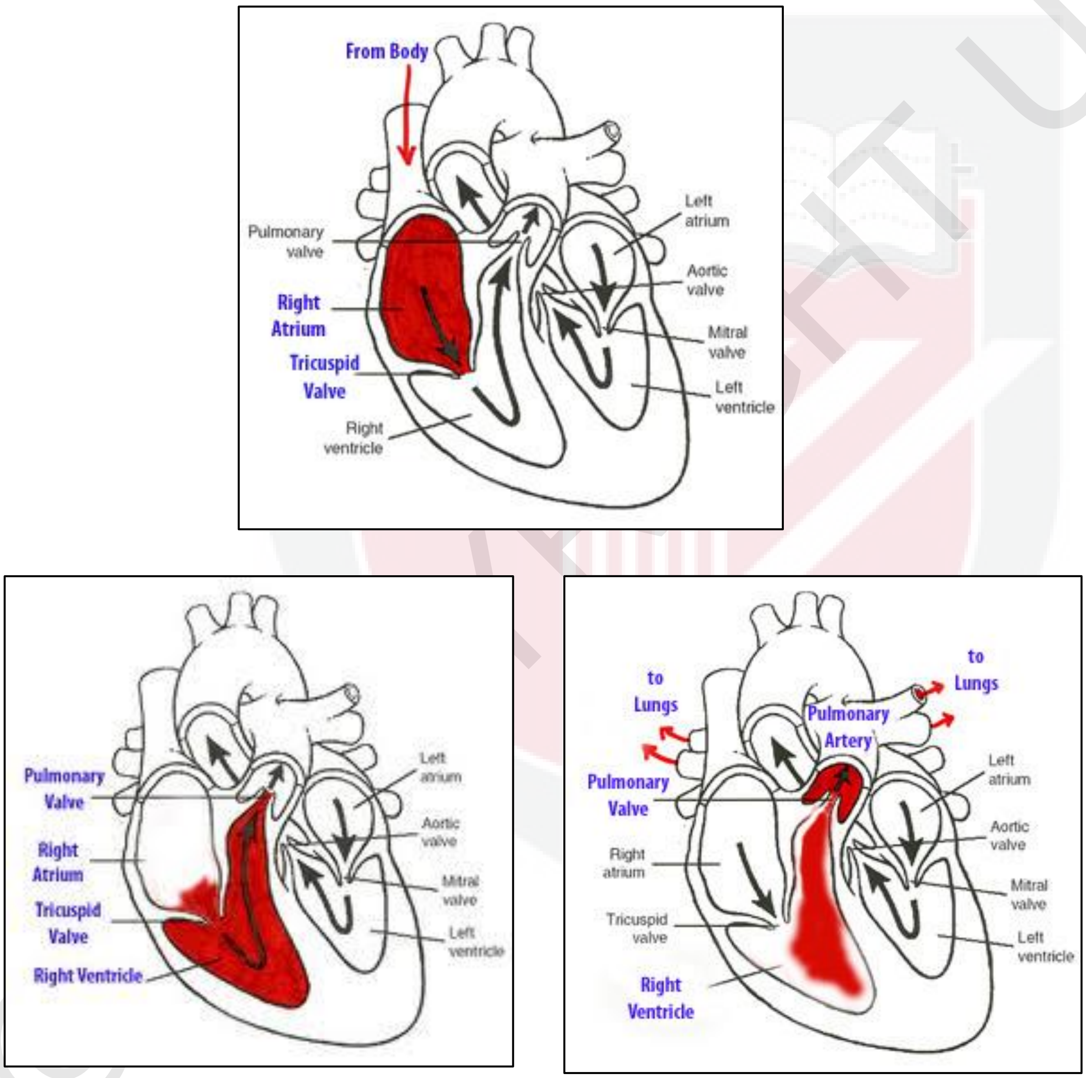

Figure 1.4: The RV blood cycle. Left: de-oxygenated blood from the body to the RV through the right atrium (RA). Centre: the tricuspid valve opens once the RA contracts. Right: the RV contracts to pump the blood to the lungs through the pulmonary artery. *http://www.bami.us/CardiacAnatomy.html*

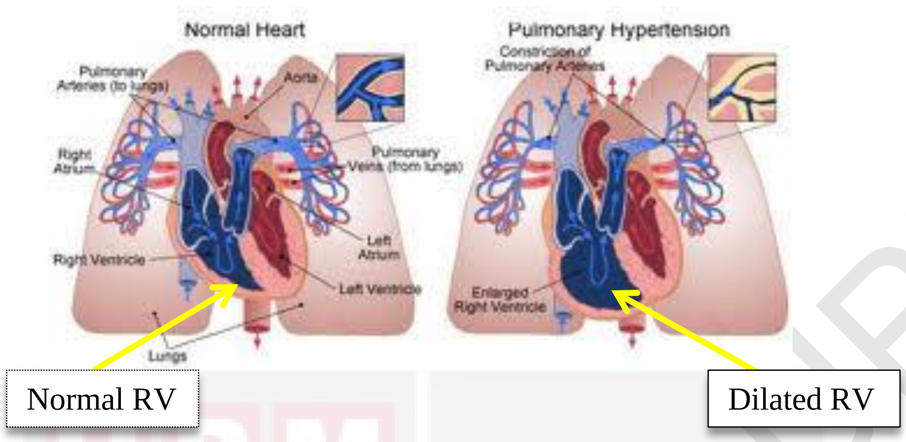

Figure 1.5: Normal pulmonary arterial (PA) to the right, and PA hypertension with an enlarged RV to the left. This figure taken from:
http://www.nationwidechildrens.org/

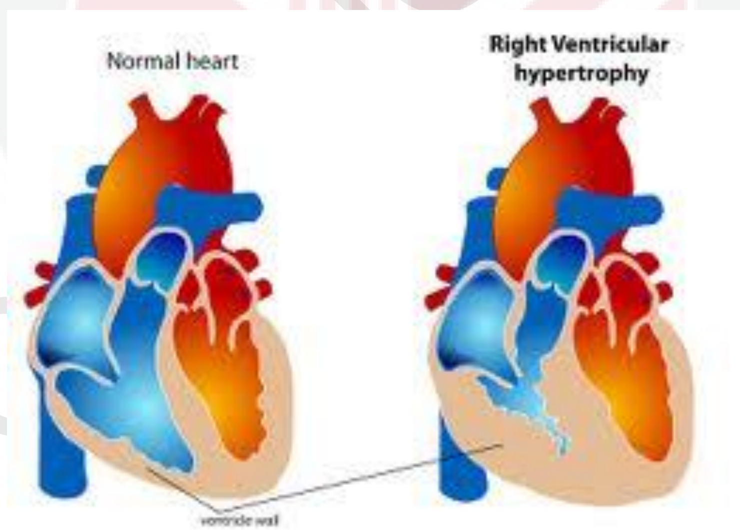

Figure 1.6: RV Hypertrophy. Niessen (2007)

Figure 1.7: Arrhythmogenic RV. Corrado et al. (2000).

Finally, the Double outlet RV (DORV) is a congenital disease of the heart which is caused by a defect in the ventricle septal (VSD). DORV leads to mixing the oxygen-poor blood with the oxygenated blood which causes heart enlargement. Generally, echocardiography gives superior sensitivity than the ECG in clinical diagnoses, where ECG may fail to give results in some RVH cases as stated by Prakash (2005).

In conclusion for this section, all of the RV diseases may lead to a change in the size of the ventricle and that could affect the RV stroke volume.

1.3 Echocardiographic Imaging Techniques and 3D Transducer

Echocardiography is a key tool and the most widely clinically used imaging technique for assessment and evaluation of cardiac structure and function. It helps with detecting different heart diseases by visualising the structure of the heart ventricles, and measuring their dimensions, masses, and to assess the wall motion velocity and its up-normality. In addition to the heart structure, echocardiography is capable of assessing normal and abnormal blood flow using a Colour Doppler, which enables the visualisation of the blood motion and diagnoses ventricle shunting and valve abnormality.

There are two types of echocardiography imaging technique; the non-invasive dynamic or freehand imaging method and Transesophageal echocardiography imaging method (TEE). The freehand imaging method is used normally for paediatric and young patients with small body surface areas (BSA), where the heart size and the distance between the probe and the heart are small. The advantages of this method are comfort, risk free, and it enables the operator to modify and guide the acquisition from different angles. However, there are many limitations with this method especially with adult patients with a thick chest, and patients with heart enlargement. In this method, the distance between the probe and the heart, the shadow of the chest bone, fat, air (in the lungs), and motion of the probe during the acquisition are all reasons that may affect the image quality according to Bosch (2006). In addition, the freehand method cannot be used during an open heart operation. On the other hand, the Transesophageal echocardiography (TEE) imaging method overcomes all the limitations of the freehand method since a cardiologist can insert the probe through the esophagus to be placed near the heart and this gives clearer images compared to the freehand method, as illustrated in Figure 1.8. TEE test lasts for around 15 minutes and it is able to give better information about the heart during surgery according to the website of the American Heart Association *http://www.heart.org/HEARTORG/*. The only limitation of the TEE method is that it cannot be used with patients who have difficulty in breathing or who have an infection in the esophagus.

Before developing the new three-dimensional echocardiography (3DE) technology, the two-dimensional echocardiography (2DE) technique was used as a key tool to assess the LV volume, function, and structure. However, the assessment and calculation formula were based on assumptions, which refer to inaccurate results from the 2DE.

Real Time Three-Dimensional Echocardiography (RT3DE) provides a fully sampled matrix-array transducer, which consists of thousands of piezoelectric elements, and each of them transmit and receive ultrasound signals, as illustrated in Figure 1.9 as given by Engås (2008).

This technique overcomes some of the limitations of the previous 2D technique and gives better quality images in 2D and 3D as stated by Bosch (2006) and Vegas and Meineri (2010). RT3DE has three imaging modes. Firstly, a Wide-Angle Mode or full volume mode acquiring the 3D image from only one shot for one full cardiac cycle. This mode is used for a specific structure such as the aortic root and mitral valve. It does not require respiratory gating.

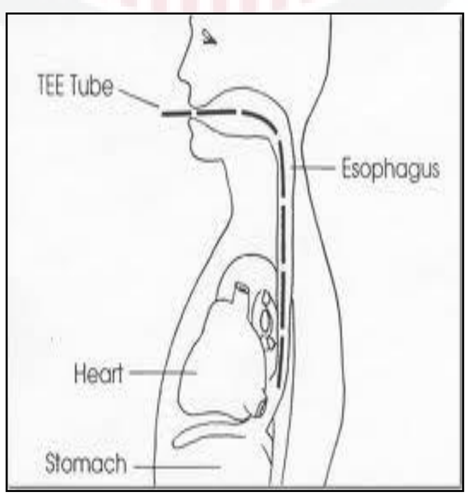

Figure 1.8: TEE, the probe inserted inside esophagus.
http://www.johnsom.com/Transoesophageal_Echo_files/.

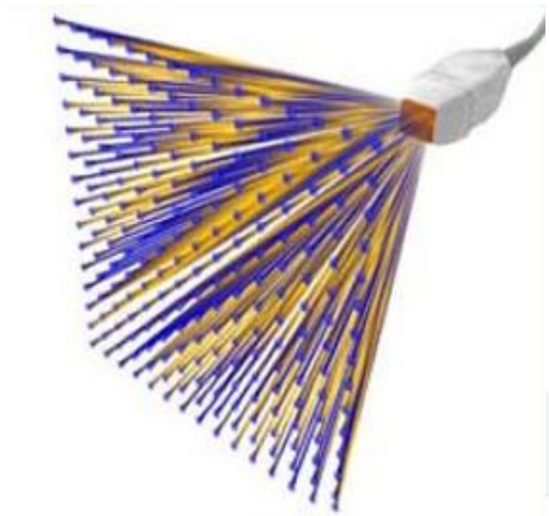

Figure 1.9: Three dimensional ultrasound transducer. The piezoelectric elements transmit and receive the ultrasound signal. This image taken from:
http://www.healthcare.philips.com/

The second mode is the Narrow Angle Mode which has superior resolution and is used normally to image the large structures that cannot be covered by the wide angle mode, according to Lang, Bandano and Tsang (2012). This mode builds the 3D images from four to seven neighbour angles and for four to seven consecutive cardiac cycles, as illustrated in Figure 1.10. Lastly there is the Magnified Mode which enables the magnified display of a subsection of the pyramidal volume as described by Bosch (2006).

RT3DE also enables the assessment of the normality or abnormality of blood using Colour Doppler imaging, which can be undertaken using the full volume or narrow angle mode.

The echocardiography imaging system consists of the following parts:

- A specifically designed probe which is registered with the machine to perform the imaging process.
- Special software designed to view, analyse, and perform measurements.
- A workstation to save and process the data that is transferred from the imaging system.

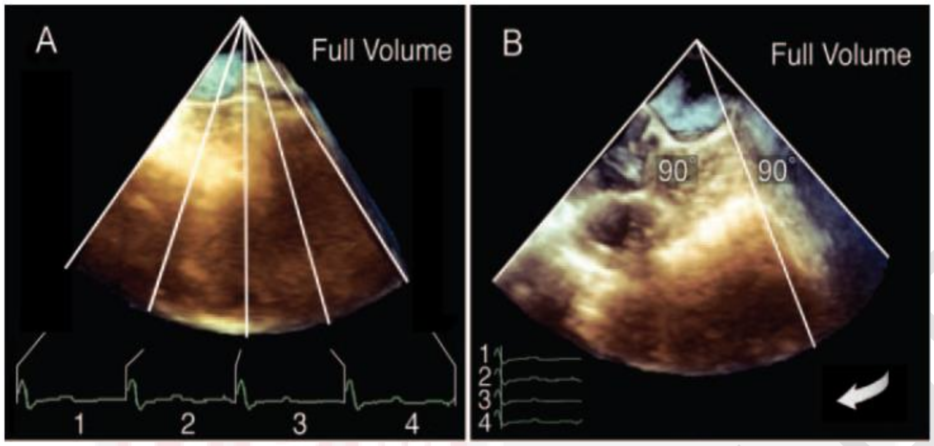

Figure: 1.10: 3D full-volume mode. (A) Gated acquisition for four consecutive cardiac cycles. (B) Stitch together each of the four sub volumes in one cardiac cycle to form one large pyramidal 3D image. Vegas and Meineri (2010).

1.4 Heart Imaging Window

The imaging window has a positive impact on the full volume provided by an acquired region and this will positively affect the assessment, measurement and diagnosing results, according to Hoch et al. (2007). It is important to explore some of the standard views of an echo system for ventricles imaging purposes. There are 20 standard TEE views as advised by the Society of Cardiovascular Anesthesiologists of America and the American Heart Association. However, in this thesis the Inflow-Outflow view is used. The inflow Tricuspid Valve (TV) and outflow Pulmonary Valve (PV) can be captured in a single plane by directing the imaging plane thru the LA 60 to 75 degrees. The probe should be located at 8-10 cm depth in the oesophagus. In this view, the Aortic Valve (AV), TV, PV, pulmonary Atrium (PA), RV outflow tract, LA and RA can be tracked. This view is used to determine the PV diseases, PA and RVOT pathology, TV diseases and ventricular septal defects (VSD).

The Inflow-Outflow view is adopted in this thesis so as to extract the full structure of the RV and to measure its volume as will be explained in detail in Chapter 4. This type of view is shown in Figure 1.11.

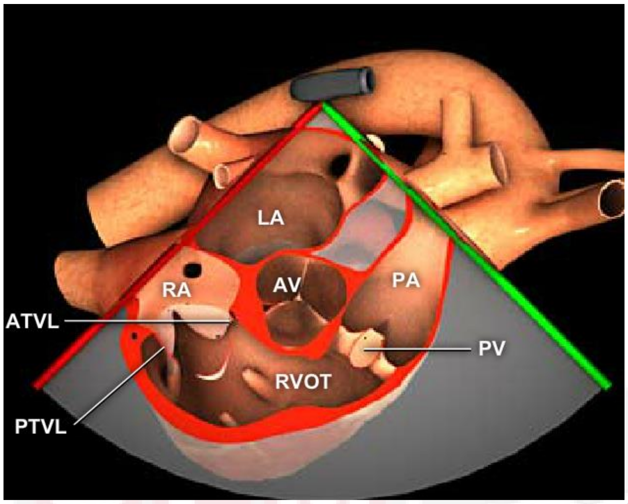

Figure 1.11: Mid Esophageal RV Inflow-Outflow, this figure is a snapshot from the website http://pie.med.utoronto.ca/

1.5 Problem Statement

The RV stroke volume is an important indicator for the abnormality assessment, diagnosing, and treatment in the clinical work. In the early days, many studies have been presented for RV volume measurement using the new technique of 4D imaging. Due to the nature of the cavity structure, position and function, most of these methods segment the RV cavity by extracting the endocardial boundary of the cavity. Manual intervention from the user was required, to determine the ED and ES stages of the cardiac cycle, by visual tracking for the cavity area, valves motion, and/or the electrocardiogram (ECG) loop. Then generated 3D model based on the extracted boundary, to approximate the cavity volume from the volume of the reconstructed surface. However, this 3D model ignores the inflow tract, outflow track, apex, and moderator band muscles. Therefore, it gives underestimated measurement of the RV stroke volume.

Therefore, a new algorithm is needed for accurate segmentation for the real structure of the RV, to satisfy measurement for the real stroke volume and 3D illustration of the RV cavity which will assist in visualising the cavity structure for initial assessment of the abnormality.

1.6 Objectives of Research

The goal of this research is to accurate segmentation of the right ventricle cavity for accurate measurement of the real stroke volume, to assist the specialists and practitioners to determine any abnormality of the RV. Thus, to achieve this goal, the following sub-objectives will be considered:

1. To introduce automatic seed point detection method;
2. To improve region growing segmentation method; by reducing processing time.
3. To design a new algorithm for automatic detection of the End-Systolic and End-Systolic stages, by tracking the changes of the segmented cavity area during a cardiac cycle; and
4. To propose a new algorithm to measure the stroke volume of the RV based on the real anatomy structure.
5. To introduce an automatic computation method for the nearest neighbours and the radius of the Delaunay ball parameter of the normal feature approximation (NormFet) method for to orienting unorganized points.

1.7 Significance of Research

However, the 3DE imaging technique gives good imaging quality in addition to the features of 3D imaging which provide the full structure of the ventricle cavity. Measuring the RV volume is big challenge because of the complexity of its geometry.

In this research, we present a ventricle stroke volume measurement by segmenting the RV from 3DE images using an improved fast single seed point region growing segmentation method for the intracardial cavity of the ventricle. An automatic approach to the determination of the seed point is used, then a novel method performed for the automatic detection of the ED and ES frame from one cardiac cycle video, to compute the stroke volume based on the intracardial structure of the right ventricle, then reconstruct 3D model of the cavity to assist the clinician in initial diagnosing.

1.8 Scope of Research

The project aims to produce a semi-automatic stroke volume measurement of the RV from 3DE moving images of one cardiac cycle, to help the specialist in the assessment of any possible RV abnormality by using real patient data. However, for the purpose of this thesis, 3D-TEE imaging is used for acquiring the patient data, and a Mid Esophageal RV Inflow-Outflow imaging view is used for imaging the ventricle cavity. To produce the full volume of the RV, with the best coverage of the entire cavity, gated-imaging of seven cardiac cycles is used in the Mid Esophageal RV Inflow-Outflow imaging view for imaging the RV cavity. The optimum 3DE data of the RV are used for input in this work. The optimum 3DE of RV data is the volume data that can show the complete entire cavity of the RV. Despite this research being focused on measuring the RV stroke volume, this work is a complete application that can be used by cardiologists for assessment of the status of the cardiac ventricles by measuring the ventricle stroke volume with possible future improvements.

1.9 Thesis Organisation

There are three styles of research structure in UPM based on the School of Graduate Studies (GSO) guide to thesis preparation (2009). The second style has been chosen for this thesis whereby a thesis is inherently divided into four parts, which are the introduction, literature review, research methodology chapters and conclusion. Each research chapter represents a separated study that has its own introduction, methodology, results and discussion. Thus, this thesis has only four research parts which complement the technical elements that form the project under discussion. Consequently, the overall organization of the thesis is as follows:

CHAPTER 1- INTRODUCTION

This chapter serves as the introductory chapter. It starts with a brief explanation of what motivated the interest to undertake this research. Next, a medical background of the anatomy of the human heart and possible diseases is presented along with the latest technique used for heart imaging since this thesis is involved with a medical problem scenario. Moreover, this chapter clarifies the problem statement, goal and objectives, and the scope of the research.

CHAPTER 2- LITERATURE REVIEW

This chapter concentrates on the literature review for the entire research. It reviews the prior research into pre-processing of the echocardiographic images, RV stroke volume measurements, segmentation methods of echocardiography imaging, End- Diastolic and End-Systolic determination methods, and 3D illustration of the RV structure from echocardiographic images.

CHAPTER 3- RESEARCH METHODOLOGY

In this chapter, the overall research methodology is explained. Furthermore, this chapter clarifies data acquisition, pre-processing of data, and gives brief details of each of the research chapters.

CHAPTER 4 – SEMI-AUTOMATIC SEGMENTATION OF THE RV CAVITY

This chapter details the RV cavity segmentation algorithm. The chapter starts with an introduction, the proposed methodology of the algorithm, implementation, results and discussion.

CHAPTER 5 - AUTOMATIC DETECTION OF THE END-DIASTOLIC AND END-SYSTOLIC FRAMES

In this chapter, details the proposed method of automatic detection for the End- Diastolic and End-Systolic stages of the cardiac cycle is presented. The chapter starts with an introduction, the proposed methodology of the algorithm, results and discussion.

CHAPTER 6 - RV STROKE VOLUME MEASUREMENT

This chapter, explain the RV Stroke Volume measurement algorithm. Starts with an introduction, proposed methodology of the algorithm, and discusses the results with validation.

CHAPTER 7 – CONCLUSION

The final chapter, concludes the whole research and highlights the contributions of this work, and proposes recommendations for future works.