AUTOMATED DETECTION OF AORTIC ANNULUS SIZING BASED ON DECISION LEVEL FUSION

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Specially dedicated to *husband, Mak* and *Abah.*

Thank you so much for your prayers.

I love all of you.

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ABSTRACT

Aortic valve disease occurs due to calcification on the area of leaflets and it is progressive over time. Surgical Aortic Valve Replacement (SAVR) can be performed to treat the patient. However, due to invasive procedure of SAVR, a new method known as Transcatheter Aortic Valve Implantation (TAVI) has been introduced, where a synthetic catheter is placed within the patient's heart valve. Traditionally, aortic annulus sizing procedure requires manual measurement of scanned images acquired from different imaging modalities which are Computed Tomographic (CT) and echocardiogram where both of the modalities produce inconsistency in measuring the aortic annulus yet able to produce different parameters which lead to accurate measurement. In this research, the image processing techniques of CT scan and echocardiogram images are done separately in order to obtain the aortic annulus size. Intensity adjustment and median filter are applied to CT scan image pre-processing, Watershed Transformation associated with the morphological operation has been used to perform the aortic annulus segmentation while image resizing and wavelet denoising method have been performed in echocardiogram image pre-processing followed by the implementation of Otsu N-clustering and morphological operation method for object segmentation. Then, Euclidean distance formula is applied to measure the distance between two points that indicates the diameter of the aortic annulus. Finally, a decision fusion technique based on the mathematical statistic approach has been applied to fuse the measured annulus size obtained from both modalities. Results affirmed the approach's ability to achieve accurate annulus measurements when the final results are compared with the ground truth. In addition, the application of non-probabilistic estimation on the decision level fusion approach which does not required the dataset training produces fast computational time and helps in determining the optimal size of new aortic valve to be implemented in human heart.

ABSTRAK

Penyakit injap aortik biasanya terjadi disebabkan oleh kalsium yang menempel di bahagian pembuka injap aorta dan ianya akan menjadi semakin kritikal yang akan mengganggu mekanisma pengaliran darah dalam jantung manusia. Pembedahan boleh dilakukan untuk merawat pesakit dimana prosedur ini memerlukan bukaan pada dada pesakit untuk menukar injap yang rosak. Walaubagaimanapun, prosedur ini berisiko tinggi dan terdapat cara yang lebih selamat untuk menjalankan rawatan iaitu dengan menjalankan implantasi menggunakan kateter. Tradisionalnya, saiz injap diukur secara manual dan pengukuran boleh dibuat pada imej yang diperoleh daripada pengimbas CT dan mesin ultrasound dimana kedua alat pengimejan ini menghasilkan ukuran yang tidak konsisten namun masing-masing mampu menghasilkan parameter yang berbeza yang dapat menyumbang kepada penghasilan ukuran yang tepat apabila digabungkan. Oleh itu, penggunaan kaedah pemprosesan imej daripada kedua-dua alatan pengimejan dilakukan secara berasingan. Kaedah pelarasan intensiti dan penapis median digunakan dalam pra-pemprosesan imej pengimbas CT, transformasi Watershed dibantu oleh operasi morfologi digunakan untuk melakukan objek segmentasi manakala kaedah pengecilan imej dan wavelet telah digunakan dalam pra-pemprosesan ultrasound imej diikuti pelaksanaan kaedah Otsu dan morfologi untuk segmentasi objek. Seterusnya, jarak antara dua titik yang mewakili diameter injap diukur menggunakan formula jarak Euclidean. Akhirnya, teknik gabungan keputusan yang berasaskan statistik digunakan untuk menyatukan diameter injap yang diperolehi daripada kedua alatan pengimejan tersebut. Berdasarkan keputusan yang diperolehi, teknik yang digunakan dalam kajian ini mampu menghasilkan keputusan yang tepat apabila perbandingan keputusan akhir dengan pengukuran manual dilakukan. Disamping itu, penggunan statistik yang bukan berasaskan probabiliti pada peringkat gabungan membantu mempercepatkan masa operasi dan membantu dalam menentukan saiz injap aorta palsu.

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LIST OF ABBREVIATION

AS	-	Aortic Stenosis
SAVR	-	Surgical Aortic Valve Replacement
LV	-	Left Ventricular
TAVI	-	Transcatheter Aortic Valve Implantation
ESC	-	European Society of Cardiology
CT	-	Computed Tomography
MRI	-	Magnetic Resonance Imaging
IJN	-	Institut Jantung Negara
PVL	-	Paravalvular Leak
BAV	-	Balloon Aortic Valvuloplasty
CE	-	Conformite Europeene
LVOT	-	Left Ventricle Outflow Tract
AA	-	Ascending Aorta
TTE	-	Transthoracic Echocardiography
TEE	-	Transesophageal Echocardiography
PLAX	-	Parasternal Long Axis
PSAX	-	Parasternal Short Axis
IWT	-	Interactive Watershed Transform
PNN	-	Probabilistic Neural Network
SVM	-	Support Vector Machine
CBP	-	Complex Back-Propagation
FCM	-	Fuzzy C-Mean
DIP	-	Digital Image Processing
SAR	-	Synthetic Aperture Radar
SBGFRLS	-	Selective Binary and Gaussian Filtering Regularized Level Set
PET	-	Positron Emission Tomography

ROI	-	Region of Interest
PSNR	-	Power Signal to Noise Ratio
AV Ann	-	Aortic Valve Annulus
Sinus Val	-	Sinuses of Valsalva
ST Jxn	-	Sino Tubular Junction
CWT	-	Continuous Wavelet Transform

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CHAPTER 1

INTRODUCTION

1.1 Background of the Research

Aortic Stenosis (AS) is the most common heart valve disease in western countries. The growth in the number of AS patients is strongly linked to the phenomenon of population ageing [1] as elder people are usually affected by this disease where typically it presents in the age of 70 years and above. The prevalence percentage of adults aged around 50 to 59 years who are likely to be affected by AS is only 0.2%, approximately. However, the number increased to 1.3% in a group of patient aged from 60 to 69 years and inclined up to 9.8% in the group of patients aged from 80 to 89 years [2]. Generally, the prevalence percentage of AS among adults over 75 years is 3% [3]. In addition, one out of eight people over 75 years are reported to have moderate or severe AS [3]. Surgical aortic valve replacement (SAVR) is the therapeutic procedure to treat patients with severe symptoms AS such as left ventricular (LV) dysfunction [4-7]. Figure 1.1 shows the percentage of adults affected by the heart valve disease according to the groups of age where the statistics can be categorized into two which are the percentage of patients who

undergo the surgery and the percentage of total prevalence of AS including patients who have gone through the surgery.

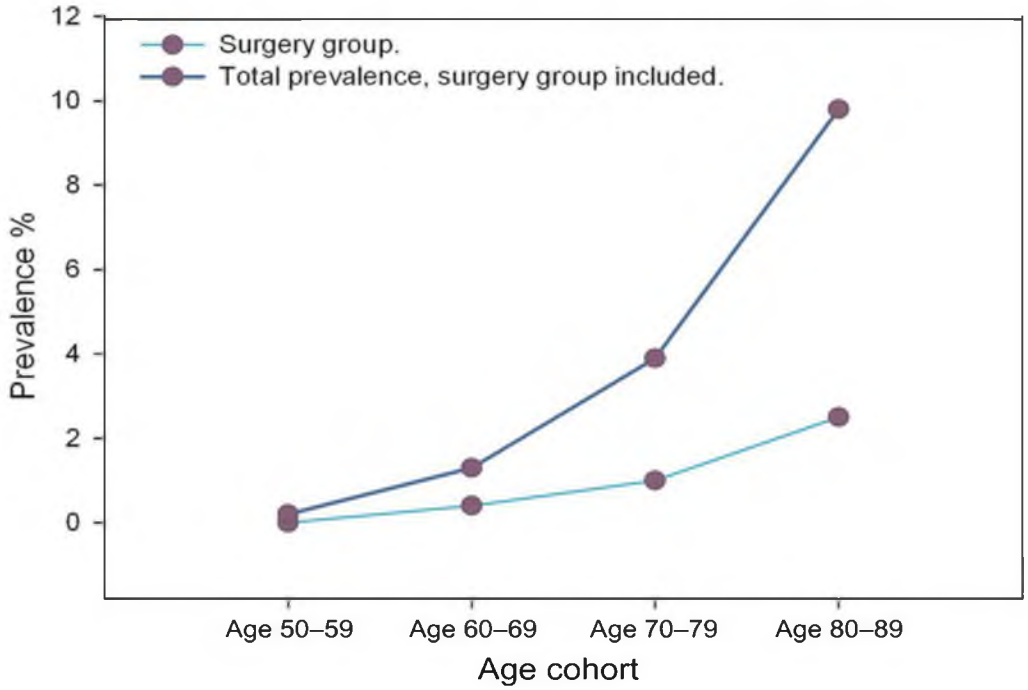


Figure 1.1: Prevalence of valvular heart disease by age [112].

AS is a high risk disease as it perceives no symptoms in the early stage of the appearance, however, once the symptoms present, it becomes progressive [4]. A study has reported that many symptomatic patients with severe AS decided not to refer themselves to the heart team for diagnosis and treatment [8]. Once the symptoms appear, untreated patients have a poor prognosis where the worsening symptoms eventually leads to death. The initial stage of AS happens due to calcification and thickening of the aortic valve leaflets that disrupt the blood flow where this condition is known as aortic sclerosis. The aortic sclerosis can be confirmed using an Echocardiogram where the changes in systemic system are noticed where the early-peaking and systolic ejection murmur are presence. About 25% of people with age more than 65 years will have aortic sclerosis where almost

17% of people with aortic sclerosis will progress to AS [9]. Approximately, the average progression time of aortic sclerosis to moderate and severe AS is 6 and 8 years respectively [10].

Once the aortic sclerosis progress to AS, several conditions may occur including severe valve thickening which happened due to calcium deposited on the area of leaflets which causes degenerative changes. As the blood starts to flow through the valve, severe calcification which caused the narrowing of the valve will restrict the blood flow to the rest of the body. This condition makes the heart work harder as the blood resistance increases the pressure in the heart and eventually causes breathlessness, chest pain, blackouts, and heart failure [11]. The average of 50% and 20% of AS patients survived within two years and five years after the onset of severe symptoms, respectively [12]. This can be seen in Figure 1.2 where it shows the progression of AS as well as the percentage of survival who managed to survive after the onset of severe symptoms within five years. It presents in a latent period where the aging process will lead to some other heart diseases which eventually lead to death.

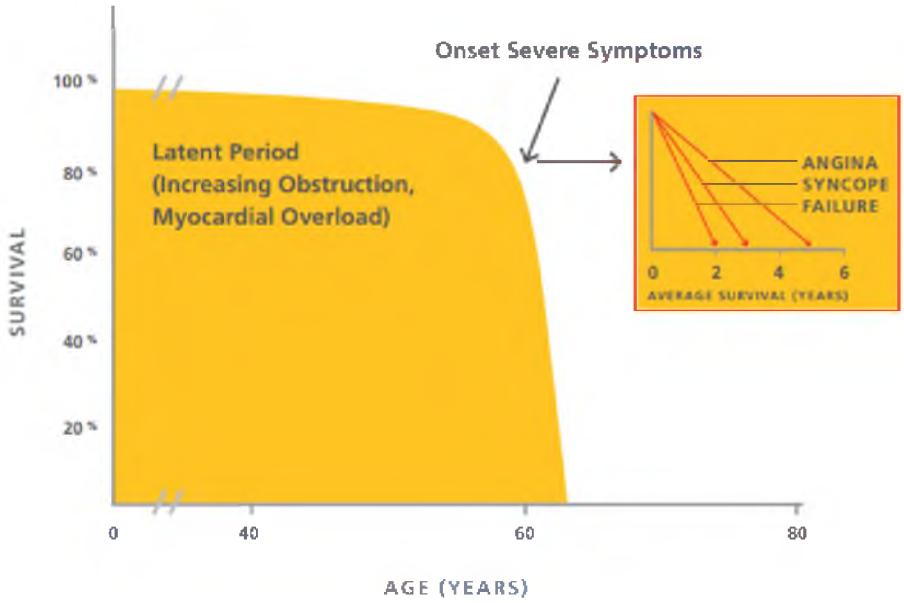


Figure 1.2: Progression of AS.

Traditionally, AS patients need to undergo the open heart surgery to replace the faulty valve with the new valve as there is no medication to slow down the progression of AS. The standard procedure to treat the AS patient is by performing SAVR. However, it is an invasive procedure that requires an open heart surgery and this procedure should be performed right after the onset of symptoms [5, 12]. Figure 1.3 shows the percentage of asymptomatic and symptomatic survival who have performed the AVR as well as the percentage of survival who have not gone through the AVR. Almost 50% of asymptomatic and symptomatic patients survived after 15 years undergone the AVR. In contrast, almost 50% of untreated patients with AS symptoms are reported to survive less than 7 years after having the AS. This proves that SAVR can improve the quality of life if the patient immediately seek for treatment [13-14].

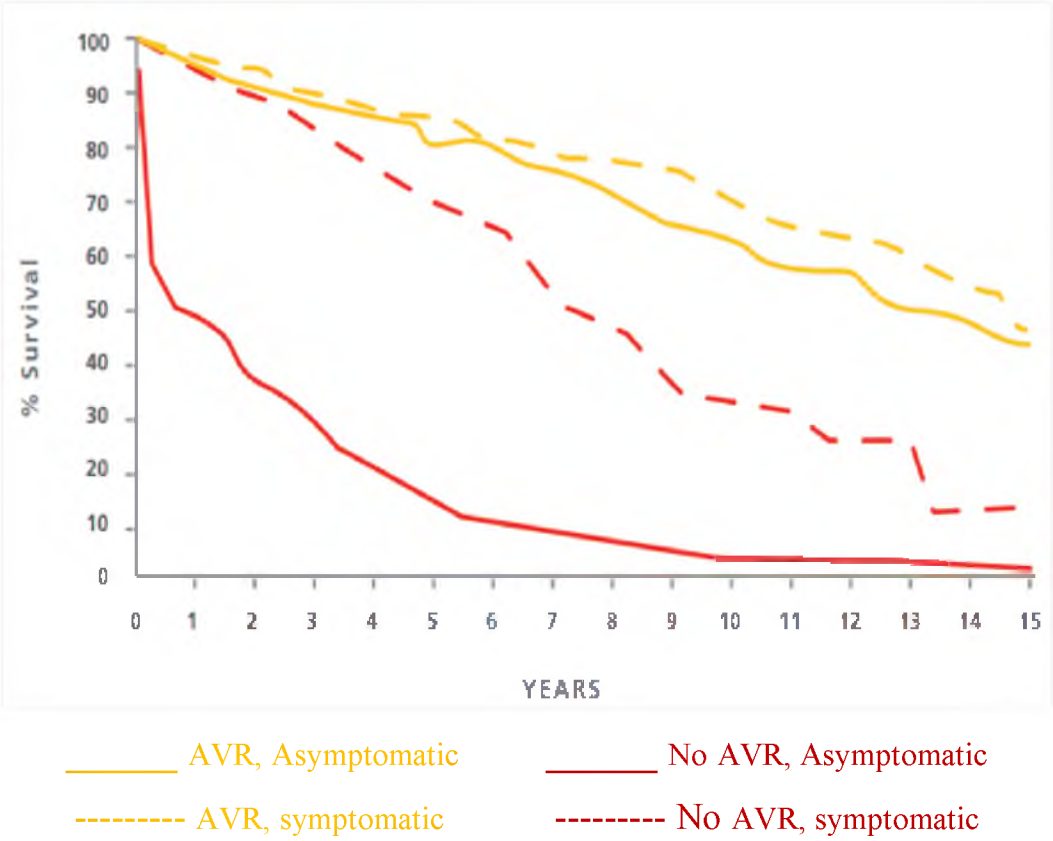


Figure 1.3: Percentage of patient survival.

In contrast, there are several reasons of why AS patients did not get the treatment and SAVR is not preferred. A survey has been conducted and reported in [13]. Figure 1.4 shows the percentage of each reason why SAVR is non-referral. Based on the chart, a few numbers of patients still doubt in undergoing the surgery while the main reason why patients refused to undergo the SAVR is due to the high risk. Treatment for older patients with severe AS are challenging as they have a higher operative risk and may reduce the life expectancy [15]. However, in recent decades, the SAVR has consistently produced a good outcomes in prolonging the patient's life as well as reducing the rate of an operative mortality [16-18]. Surgery will benefit the patients depending on their health condition themselves as stated in Euro Heart Survey with 33% of patients with severe AS are not candidates for SAVR. It is due to the pre-existing comorbidities, frailty, and disabilities [19]. Therefore, despite of having good results of valve surgery, there may be another alternative ways where the treatment is less invasive and would be beneficial for patients with various conditions of their health.

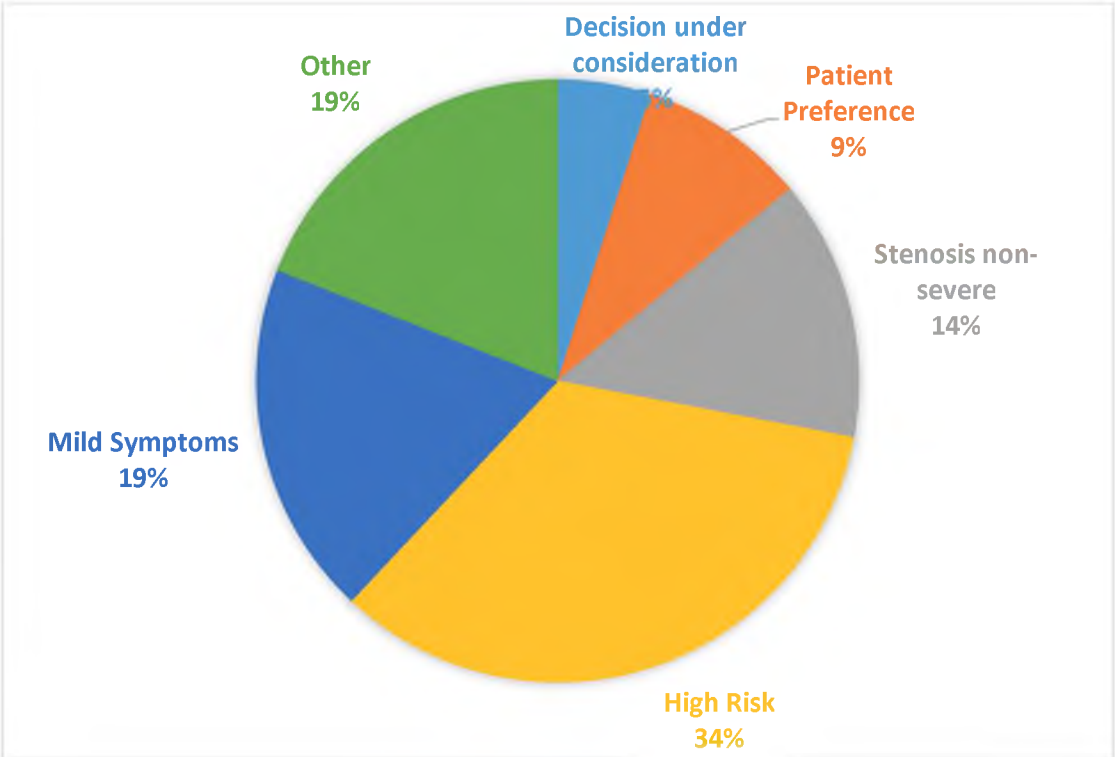


Figure 1.4: Reasons of why AVR is non-referral.

Transcatheter Aortic Valve Implantation (TAVI) has been developed as a promising alternative to conventional valve replacement for patients with severe, symptomatic AS who are otherwise left untreated due to the perceived high risk of operative mortality [20]. TAVI is less invasive compared to SAVR as it does not require an open heart surgery in the procedure. The strategy of new valve insertion can be divided into two common routes; transfemoral where the new valve is inserted through the femoral artery and transapical which goes through a small cut on the left side of patient's chest to reach the apex of the heart.

In order to determine whether the TAVI procedure would benefit the patients, several diagnoses or tests can be performed by referring to the guidelines proposed by the European Society of Cardiology (ESC) [13]. Once the decision has been made, TAVI candidates need to be examined using several medical imaging modalities such as computed tomography (CT) scan, angiogram and magnetic resonance imaging (MRI) in order to measure the anatomy of valve structure. In addition, these kinds of modalities may help in determining the selection of the suitable prosthesis valve to be implanted.

1.2 Problem Statement

Without appropriate aortic valve replacement, AS patients with severe symptoms will have high mortality where the percentage of mortality is 3% to 4% soon after symptoms have appeared and 7% among patients who are waiting for the SAVR [21]. In addition, a significant number of patients with some other pre-comorbidities are not recommended to undergo the SAVR as it will not benefit them. Thus, this will cause the AS patients with severe symptoms to be left untreated. As TAVI has been proposed as an alternatives to SAVR, AS patients still have a chance to survive and have a good quality of life.

In regards of the matter, the evaluation of the anatomic characteristics of the aortic valve is critical in determining the TAVI's success. Annulus size and shape vary for every patient. Figure 1.5 illustrates the different structures of normal and abnormal aortic valve. Basically, the normal aortic valve will have a proper opening and closing of the leaflets while valves that has been severely calcified yield an improper opening and closing of the leaflets. Currently, the procedure to determine the size of the prosthetic valve is done manually by experts. Common diagnosis includes the use of Echocardiogram and CT scan imaging modalities. Severe AS patients can be assured by referring to the characteristics provided by the Echocardiogram modality such as the aortic valve area, indexed valve area, mean transvalvular pressure and velocity ratio.

In addition, all those information are obtained in real time measurement which provides high accuracy results. However, when it comes to measuring the size in space which is in real time 2-D Echocardiogram image, it needs to be done manually and still requires experts. Besides, Echocardiogram modality is highly operator-dependent. It usually has limitations on its resolution and always suffer from speckle noises as it deals with real time measurement. This will affect the measurement accuracy as well as lead to deployment of wrong size of prosthetic valve. Figure 1.6 shows the normal and abnormal aortic valves in Echocardiogram images where the red circle inside images represents the area of aortic annulus.

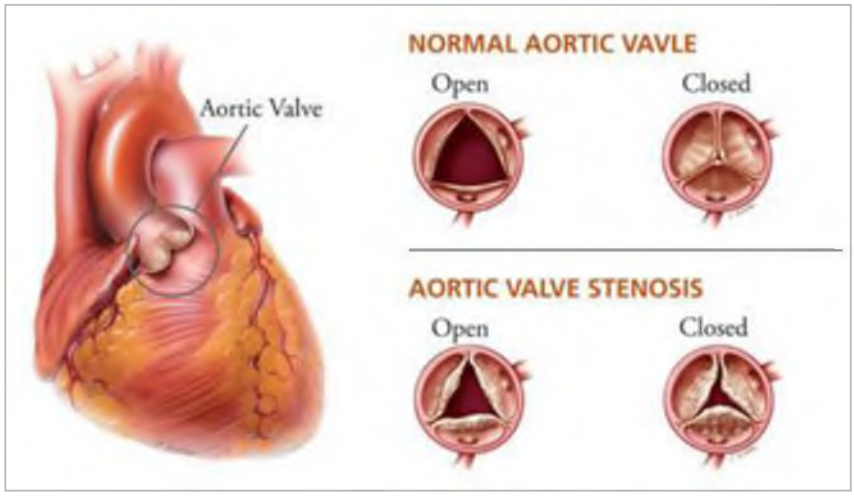
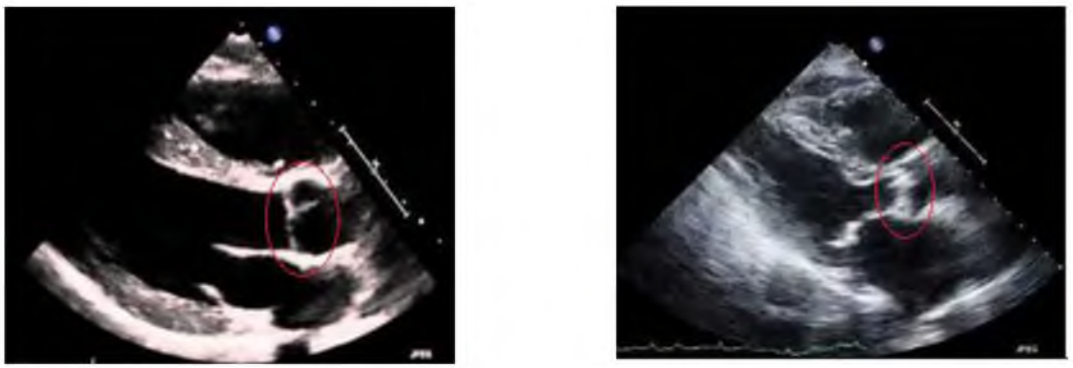


Figure 1.5: Normal and abnormal aortic valve.

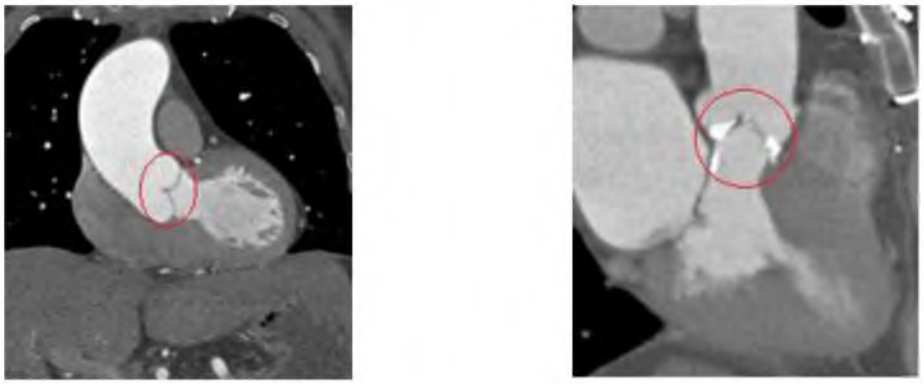


(a) (b)

Figure 1.6: (a) Normal and (b) Abnormal aortic valve in Echocardiogram image.

Meanwhile, CT scan modality is often used to further evaluate an abnormality seen on other tests such as an X-ray or an Echocardiogram. CT scan produces cross-sectional images that appear to open the body up, allowing the doctor to look at it from the inside. It is able to create a detailed picture of heart and its blood vessels. However, CT scan is prone to calcification. A soft thrombus can be partially covered and masked by contrast. Then, errors are possible. Figure 1.7 shows the normal and abnormal aortic valve in CT scan modality where the red circle in image (a) shows the area of valve that

has no calcium deposited on it while image (b) shows the AS that has been severely calcified.



(a) (b)

Figure 1.7: (a) Normal and (b) abnormal aortic valve in CT scan image.

Based on the characteristics from both CT scan and Echocardiogram image, each of them produces important features which are useful in order to measure the diameter of aortic annulus as well as choosing the appropriate size of prosthetic valve before performing the TAVI procedure. Currently, pre-TAVI procedures are performed manually by the specialists and require a lot of work and procedures as well as time-consuming to ensure the success of TAVI. Therefore, in this research, the applications of digital image processing associated with the decision fusion technique has been used in order to reduce the workloads and human error.

Basically, the framework includes four stages of processing which are image enhancement, object segmentation, annulus measurement and decision fusion. The proposed algorithms are applied to both CT scan and Echocardiogram image separately. Final features refer to the measured size of aortic annulus from CT scan and Echocardiogram image obtained after performing the object segmentation. Decision fusion approach is chosen as the best fusion technique to fuse this two features in order to obtain the exact size of prosthetics valve that should be implanted into human heart. This

is due to other fusion approaches such as data/image and features fusion which are not well-matched with the obtained final data.

1.3 Objectives of the Study

The following are the objectives of this study: -

i. To perform automated segmentation of aortic annulus using cardiac CT scan and Echocardiogram image separately.
ii. To predict the diameter of segmented aortic annulus.
iii. To perform decision fusion of annulus size obtained from CT scan and Echocardiogram in order to attain a more precise dimension of aortic annulus.

1.4 Scope of the Study

The scope of this research includes the measurement of the aortic annulus size of human heart in 2D image obtained from both CT scan (Dual-source Somatom Definition, Siemens, Germany) and Ultrasound (Philips) imaging modalities. The original file type of DICOM is converted to JPEG with size of 550 x 550 for CT and 600 x 800 for Echocardiogram image. Datasets of four patients which have been obtained from Institut Jantung Negara (IJN) are tested using the proposed approach where all of the Echocardiogram images are captured from the parasternal long axis (PLAX) view. In addition, all of the datasets are from the patients who will undergo TAVI procedure and the size of aortic annulus obtained from their measurement will constitute a ground truth in this experiment. Therefore, a validation can be made by comparing the proposed approach to the ground truth. The 64-Bit MATLAB software version of R2016a and an

operating system of Window 8.1 with Intel core i5 processor are used to perform the analysis.

1.5 Significance of Study

TAVI is regarded as an advanced technology in the medical field to treat patients with severe aortic valve disease through blood vessel. Presently, the size of the prosthetic valve is chosen based on the manual measurement on CT scanned image performed by the experts, and the verification of the selected size may also be done using Echocardiogram. False determination of annulus size may cause serious complications for TAVI where deployment of a large valve may cause incomplete opening and closing of leaflets, and excessive oversizing can lead to annular rupture, while deployment of a small valve can cause paravalvular leak (PVL). Therefore, in this research, a new framework is introduced to perform an accurate measurement as well as to overcome the disparity or wrong aortic annulus measurement. TAVI procedure is less invasive as it does not require an open heart surgery. AS patient with severe symptoms will still have a chance to live in a good quality as this procedure has been proven to produce promising results to the TAVI patients. Besides, this research also helps the clinicians in solving uncertainty in a short time as the approach is efficient and produces a faster results in determining the exact size of prosthetic valve that should be implemented in human heart. Thus, hopefully this will help in alleviating the constraints before performing the TAVI procedure in Malaysia.

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