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Wavelet-based Aortic Annulus Sizing of Echocardiography Images

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***Abstract*—Aortic stenosis (AS) is a condition where the calcification deposit within the heart leaflets narrows the valve and restricts the blood from flowing through it. This disease is progressive over time where it may affect the mechanism of the heart valve. To alleviate this condition without resorting to surgery, which runs the risk of mortality, a new method of treatment has been introduced: Transcatheter Aortic Valve Implantation (TAVI), in which imagery acquired from real-time echocardiogram (Echo) are needed to determine the exact size of aortic annulus. However, Echo data often suffers from speckle noise and low pixel resolution, which may result in incorrect sizing of the annulus. Our study therefore aims to perform an automated detection and measurement of aortic annulus size from Echo imagery. Two stages of algorithm are presented – image denoising and object detection. For the removal of speckle noise, Wavelet thresholding technique is applied. It consists of three sequential steps; applying linear discrete wavelet transform, thresholding wavelet coefficients and performing linear inverse wavelet transform. For the next stage of analysis, several morphological operations are used to perform object detection as well as valve sizing. The results showed that the automated system is able to produce more accurate sizing based on ground truth.**

***Keywords*—aortic; stenosis; TAVI; annulus; sizing; echocardiogram; denoising; detection.**

I. INTRODUCTION

One out of eight people aged over 75 years are reported to suffer from heart disease including Aortic Stenosis (AS) [1]. This disease is common in developed countries [2]. AS is categorized as a high risk disease which may cause death to the patients as it perceives no symptom in the very beginning of the presence, but it progresses rapidly once the symptoms have appeared [3]. As a patient grows old, calcium may deposit on the valve where this complication is known as aortic valve calcification. This will lead to the narrowing of the aortic valve opening that may cause inadequate blood flow pumped by left ventricle through aorta toward the whole body. Fig. 1 shows the opening and closing structures of aortic valve. The left image represents normal heart valve without calcification while the right image shows the abnormality of the valve where it has been severely calcified. Normal heart valve shows a proper closing of aortic valve while calcified valve is vice versa.

Symptoms of AS include chest pain, heart failure for instances paroxysmal nocturnal dyspnea, orthopnea, dyspnea on exertion, and shortness of breath and syncope where it often occurs upon exertion when systemic vasodilatation in the presence of a fixed forward stroke volume causes the arterial systolic blood pressure to decline [4-5]. In order to improve the number of survival among AS patients, SAVR can be performed [3]. However, in clinical report, at least 30% of severe symptomatic AS patients will not undergo the surgical replacement of the aortic valve as the open heart surgery might give high risks to the patients due to their age, where usually a person over 75 years old are prohibited to undergo this procedure. Besides, other conditions such as dysfunction of left ventricular, or the presence of multiple coexisting conditions will cause operative mortality [6-9]. Therefore, a less invasive treatment for these kind of patients can be an alternative to treat the patients with severe AS.

II. IMAGING MODALITIES

A. Transcatheter Aortic Valve Implantation (TAVI)

The TAVI techniques have been proven to be a realistic alternative therapy to Surgical Aortic Valve Replacement (SAVR) [11]. TAVI involves inserting a new artificial heart valve inside the old valve that is severely calcified using a balloon catheter. The contribution of several imaging modalities helps in selecting the exact size of prosthesis valve design by a manufacturer. The devices that can be used are echocardiogram and computed tomography (CT) scan. Transthoracic echocardiography (TTE), transesophageal echocardiography (TEE), multislice computed tomography (MSCT) and angiography are all of the common imaging techniques which can be used to evaluate aortic valve function and anatomy. The importance of measuring the accuracy of aortic annulus for TAVI has been long stressed in literature [12]. The term 'sizing' indicates the choice of prosthesis that is in the range of available sizes that best fit into the native valve root. This measurement is considered difficult due the dynamic changes of aortic annulus in the patient during the systolic and diastolic phases [12]. To obtain the size of the aortic annulus, the most conventional method is to calculate the aortic root and the geometry of LVOT [13].

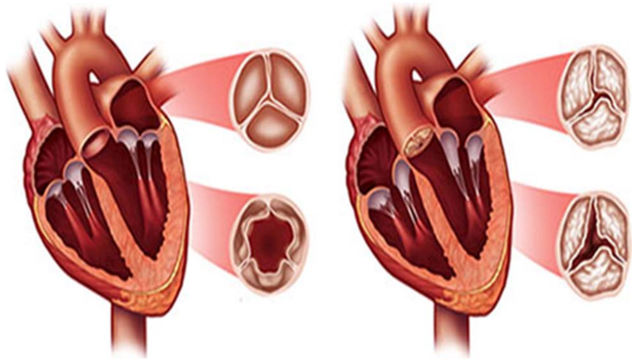

Fig. 1. Closing and opening structures of normal valve (left) and valve with aortic stenosis (right) [10].

Fig. 2 shows the parasternal long axis view of aortic annulus where the annulus is located between aortic root and left ventricular outflow tract (LVOT). Blue label shows the distance of annulus that represents the diameter of aortic valve. Fig. 3 shows the measurement of aortic annulus in real data image where yellow line shows the manual marking of annulus distance. However, the measurement obtained from real data should be referred to the available size of prosthetic valve offered by the manufacturer.

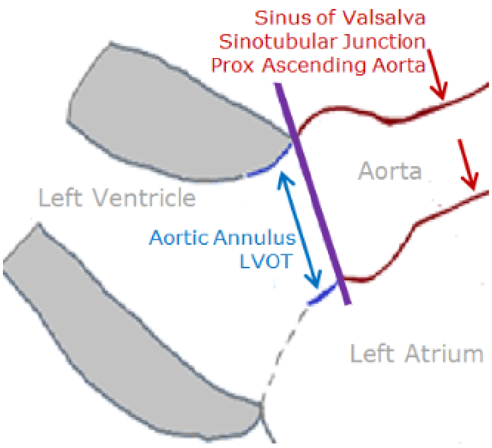

Fig. 2. Parasternal long axis view of aortic annulus [14]

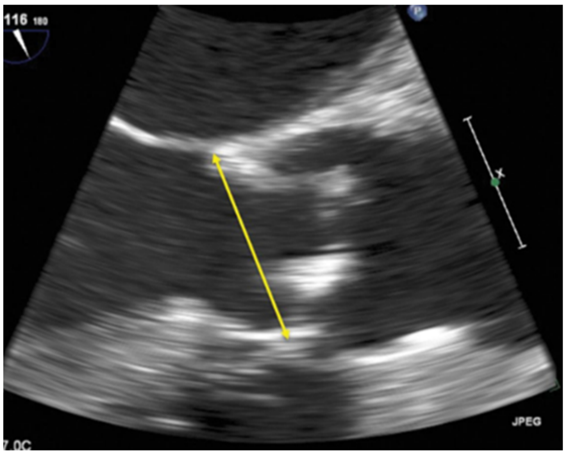

Fig. 3. Manual measurement of annulus on Echocardiogram image

Incorrect deployment of new prosthetic valve may cause fault in positioning the aortic valve. Large deployment of a new valve will interrupt on the anterior mitral valve leaflet and disturb proper functioning of the mitral valve apparatus while small deployement may embolize into the aorta and block the coronary arteries. As a result it may lead to paravalvular leaks. Therefore, the selection of exact size of new prosthetic valve is important to avoid those failures.

The available sizes for an Edwards SAPIEN prosthetic valve are 23mm, 26mm and 29mm while for CoreValve, sizes that are available are 23mm, 26mm, 29mm and 31mm. Table I. shows the size of new prosthtetic valve that is provided by the manufacturer based on the measurement obtained from Transesophageal echocardiography (TEE). There will be a several ranges of TEE measurement that fits the size designated by provider. However, in some cases, when there is a conflicting measurement of aortic annulus sizing due to asymmetrical calcifications or eccentric leaflets, balloon aortic valvuloplasty (BAV) will be used as an alternative of TEE to confirm any uncertainties [15].

B. Application of Ultrasound imaging in Medical Image Processing

Ultrasound is also categorized as imaging modalities where it uses sound wave to capture the organ structure in human body. The use of ultrasound in medical field is said to be safe as it does not contribute any radiation to the patients. Unlike other imaging modalities such as CT scan and x-ray, ultrasound uses a high frequency of sound wave and it is a non-invasive imaging method. Therefore, it is preferred to be used in viewing a development of the fetus of pregnant women as it would protect the mother and the baby from ionized radiation that could give side effects like premature baby born.

However, the diagnostic of using the ultrasound technique are not limited. It has been successfully used to perform a diagnosis on the other organs inside human body. For instance, ultrasound is also used to detect a breast cancer, lung nodule, and determine the abnormality of the kidney based on its size. Apart from that, ultrasound technique could also be used in diagnosing the heart disease. Echocardiogram is applied to human heart where it uses the same principle as ultrasound [16].

TABLE I. CORE VALVE AND EDWARD SAPIEN PROSTETIC VALVE* [15]

CoreValve	**23 mm**	**26 mm**	**29 mm**	**31 mm**
TEE (mm)	17 – 19	19 – 22	22 – 26	25 – 28
Edward SAPIEN XT	**23 mm**	**26 mm**	**29 mm**	**-**
TEE (mm)	18 - 21	22 – 24	25 - 27	-
Edward SAPIEN	**23 mm**	**26 mm**	-	-
TEE (mm)	18 - 21	22 – 24 (25*)	-	-

*Recommended by the manufacturer. For uncertain cases, use balloon aortic valvuloplasty (BAV) for confirmation.

Diagnostic procedure can provide important information including the shape of the heart, chamber size and other abnormalities. It can also provide useful information on heart valve disease. However, ultrasound is a medical device that depends on the experts to obtain a decent visualization of the diagnosis. The quality of captured image will definitely depends on the operator. Besides, other factor influencing the quality of the image is due to high resistance of human tissue that limit the penetration and reflection of the sound signal. The resistance may lead to noisy image. Therefore, the application of Digital Image Processing (DIP) on denoising the image may help in producing a better quality of captured image. Consequently, a qualitative and quantitative measurement can be implemented to the denoised image [16]. Qualitative measurement is used to determine the position or location of the object interest while quantitative measurement may give an information on the size, area and volume of the anatomical structure.

Filtering or denoising the input data especially on echocardiogram datasets is a necessary procedure before proceeding to the next step of analysis as it will determine the quality of end product which is the detection or segmentation result for instance. There are three main types of filters discussed in [17], it can be used to remove the speckle on the input image which are wavelet analysis, anisotropic diffusion, and Synthetic Aperture Radar (SAR). The use of Wavelet to perform an image denoising is promising as the analysis result will remove the noise and preserve the original characteristics of the input including its frequency content. The details explanation has been discussed in [18] while the anisotropic diffusion which is also known as Perona Malik diffusion, is a method of reducing the image noise while preserving a significant parts of the image content such as edges and outline of the object.

The SAR method is actually based on a multiplication of reflectivity and speckle noise [17][19-20]. These methods assume statistical independence of noise and reflectance. These filters also make the assumption that the ratio of noise standard deviation to mean is constant throughout the image. Image segmentation of ultrasonic image can be categorized into two main basic properties which are edge based approaches and region based approaches. The edge based approaches will be based on the abrupt sudden changes in intensity while the region based is similar to the other approaches but according to predefined criterion [21].

There are many publications on region based approaches half of a decade ago. One of them is a fast adaptive B-spline snake algorithm is introduced to extract the left ventricular echocardiographic images, where the algorithm is used a combination of external forces, adaptive node insertion, and multiresolution as their strategy [22]. Apart from that, a segmentation of features using watershed transform is performed in [23] where the input is being filtered out using log filter to avoid over segmentation. The other promising and comprehensive framework has been published recently where the aim of the research is to detect a thrombus by using a region based method [24]. Initially, the speckle noise is filtered out using Lee Filter and image is segmented using active contour method to detect a left ventricular. Other method used in segmenting the echocardiographic based on a combination of edge based and region based approaches has been discussed in [25]. In this framework, they are introducing a segmentation and detection of ventricular border on 2D echocardiographic images automatically by combining two well-known methods which are k-means clustering and active contour model. Segmentation of the object is achieved by implementing the clustering algorithm and features are extracted using the active contour. In this research, a wavelet method will be used to smooth and remove a speckle noise in the image. Analysis is then proceeded with region based segmentation and features are extracted using morphological operation.

III. Proposed Framework

In this paper, the application of most promising and frequent technique of image filtering which is wavelet denoising algorithm is used. The framework is divided into three stages of processing where at the beginning the features are extracted first followed by image filtering and annulus measurement. Fig. 4 shows the steps of proposed framework. The 2-Dimensional image of echocardiography acquired from parasternal long axis view with size of 434 × 636, which can be seen in Fig. 3 is experimented in this system and the total number of images tested on this algorithm are nine.

A. Pre-processing Stage

In this stage, data size reduction and image denoising are applied as a part of feature extraction. The reduction of data size consists of two steps. Generally, the raw echocardiographic image may have patient information as well as some other information regarding the technical parameter set-up by the system. By remaining all those information, this would result in an ineffective feature extraction and give low accuracy in segmentation as those information are considered as noise. To extract the features, first the original dimension of the raw data image which includes the overall area of active echo cone is separated from those unrelated information.

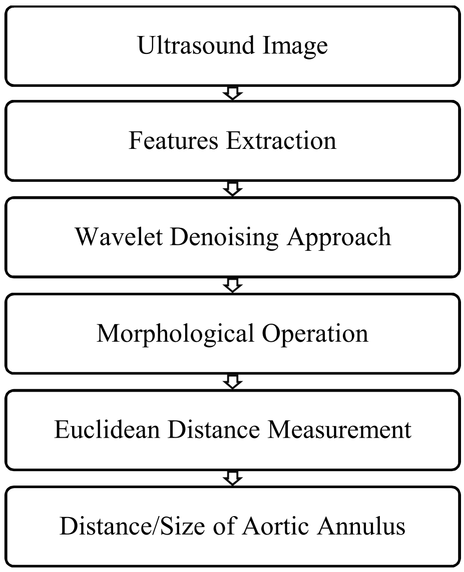

Fig. 4. Methodology of research

In this analysis, a fixed data size of 256×256 is considered to represent well-shape of region of interest which determines the exact location of aortic annulus. This task allows a significant reduction of the computational time, assisting in the achievement of the long term goal of real time cardiac assessment. Fig. 5 (a) shows the echocardiographic image data after size reduction where the ROI is marked using the red line. Fig.6 shows possible measurement that can be made along the ascending aorta which contributes three main parts of it. They are the aortic valve annulus (AV ann) level, sinuses of Valsalva (Sinus Val), and Sino tubular junction (ST Jxn) from long-axis view. Usually this view can be found at an angle of approximately 110 to 150 degrees. Annulus is measured by convention at base of aortic leaflets [26].

Image denoising using wavelet thresholding method allows an adaptive representation of signal discontinuities. Wavelet transform has been widely used in many applications due to its advantages. Generally, wavelet transform is used to decompose the signal into high and low frequency component. The wavelet coefficient denotes a measure of similarity in the frequency content between a signal and a selected wavelet function [27]. These coefficients are computed as a convolution of the signal with the scaled wavelet function that can be interpreted as a dilated band-pass filter [27].

Practically, the implementation of wavelet transform associated with the perfect reconstruction of filter bank using orthogonal wavelet family results in the decomposition of the signal into sub-signals which corresponds to the different frequency contents. Several types of wavelets which provide the orthogonality properties include Symlets, Daubechies and Coiflets [27].

(a) (b)

Fig. 5. Echocardiographic of (a) raw image and (b) denoised image

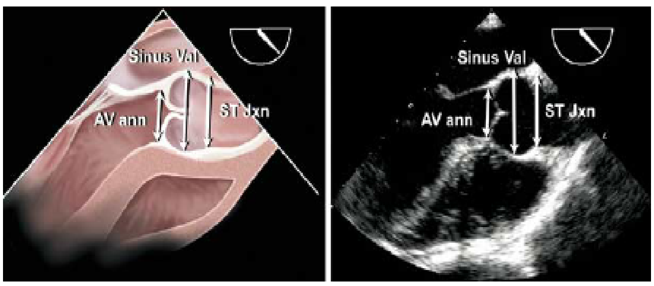

Fig. 6. Features along ascending aorta including aortic annulus (AV ann), sinuses of Valsalva (Sinus Val) and sinotubular junction (ST Jxn) [25]

Initially, wavelet transform is introduced for the time-frequency analysis of continuous signals. It is then extended based on the theory of multi-resolution wavelet transform which depends on the FIR filter approximation. This can be achieved using the dyadic form of continuous wavelet transform (CWT) where in dyadic form, the scaling function is chosen as power of two [26]. Then, the discrete wavelets $\psi_{m,n}(t) = 2^{\frac{-m}{2}}\psi(2^{-m}t - n)$ are used in multi-resolution analysis creating an orthonormal basis for L_2 ($\Re$) [27]. Initially, if the noise is assumed as stationary, an observing recorded signal that is corrupted by additive noise can be represented as;

$$y(i) = x(i) + \sigma\varepsilon(i), i = 0,1,\ldots,n-1 \quad (1)$$

Where $y(i)$ is noisy signal, $x(i)$ is noise free actual signal and $\varepsilon(i)$ are independently normal random variables and σ represents the intensity of the noise in $y(i)$ [27]. Decomposition of signal, $x(t)$ into low and high frequency components are named as approximation coefficients and detail coefficients respectively. Thus, the reconstruction of $x(t)$ can be written as;

$$x(t) = \sum_{k=-\infty}^{\infty} D_m(k)\psi_{m,k}(t) + \sum_{k=-\infty}^{\infty} A_l(k)\phi_{l,k}(t) \quad (2)$$

Where , $\psi_{m,k}(t)$ is discrete analysis wavelet, and $\phi_{l,k}(t)$ is discrete scaling, $D_m(k)$ is the detailed signal at scale 2^m , and $A_l(k)$ is the approximated signal at scale 2^l. $D_m(k)$ and $A_l(k)$ is obtained using the scaling and wavelet filters [27]. The differences between different mother wavelet function for example Haar, Daubechies, Coiflet and Symlet corresponded to how these scaling signals and the wavelets are defined. The relation between low-pass, $h(n)$ and high pass filter, $g(n)$ can be stated as follows;

$$h(n) = 2^{-\frac{1}{2}}(\phi(t), \phi(2t - n))$$
$$g(n) = 2^{-\frac{1}{2}}(\psi(t), \phi(2t - n)) \quad (3)$$

Therefore, relation between $h(n)$ and $g(n)$ is not independent to each other, they are related by $g(n) = (-1)^n h(1-n)$.

Wavelet thresholding method involves three steps in performing the image denoising. The image is first transformed using the linear discrete wavelet transform followed by the non-linear thresholding method. In this step, each of the wavelet coefficient is thresholded by comparing the value with the initial threshold limit. If the coefficient is smaller than threshold value, then it is set to zero otherwise it is kept or modified. By replacing all of the small coefficients with zero, it may reduce the noise. Finally, a linear inverse wavelet transform is applied to the threshold image to perform the image reconstruction where the essential signal characteristics are well-preserved.

The selection of threshold value is important as it determines the percentage of noise reduction in the image. In this analysis, hard thresholding function is applied instead of soft thresholding. It works by choosing all wavelet coefficients which are greater than the initial threshold limit and setting the others to zero. The type of mother wavelet used is Daubechies as it is widely used in solving the signal discontinuity. Four levels of decomposition are applied. Higher level may lead to loss of features while lower level produces inappropriate noise reduction. Fig. 5 (b) shows the denoised image after performing the wavelet thresholding. The image shows that all the edges are well preserved and noises are successfully supressed while Fig. 7 shows the wavelet decomposition of four levels.

B. Segmentation stage

After performing the image denoising using wavelet thresholding method, processed image is converted into a binary image. This is the initial steps of applying the morphological operation for image segmentation as it required a data image in binary. Fig. 8 (a) shows the binarization of denoised image where the greyscale components are converted into binary '0' and '1'. Image skeletonize is a thinning process [28]. It removes pixels on the boundaries of the objects but keep the objects to break apart. The pixels remaining make up the image skeleton. The advantage of this thinning method is determined by how much the skeleton is extracted and preserves the topology of the shape without any interrupt. Fig. 8 (b) shows the output image after skeletonizing the binary image. An additional morphological operation is used to shrink all the branches into a point. This remains the main body of the region of interest (ROI).

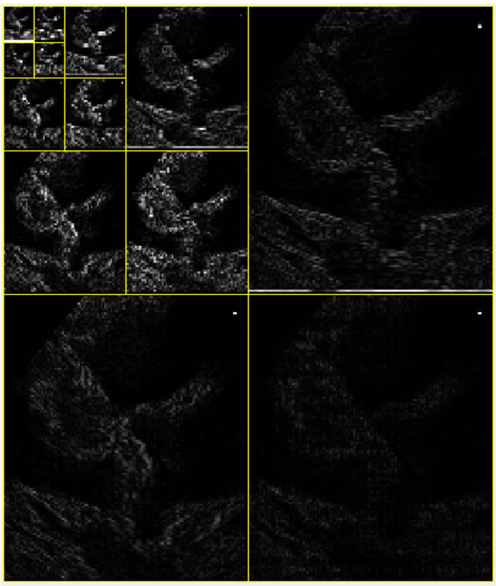

Fig.7. Four level of wavelet decomposition

(a) (b)

Fig. 8. (a) Binarization of denoised image and (b) skeletonization of binary image

C. Aortic Annulus Measurement

Finally, the distance of aortic annulus is computed based on Euclidean distance. The intersection point between ascending aorta and LVOT indicates the actual distance of annulus. The previous output is first being skeletonized followed by shrinking the skeleton image using morphological operation. An automated measurement can be performed by obtaining the distance between two intersection points of the main body which locates the ROI. Both of the points are representing the annulus distance. In order to illustrate the distance between two intersection points, Fig. 9 shows the measurement of annulus distance obtained in pixel using MATLAB tool. As a processed image is obtained in pixel, this value needs to be converted into millimeter (mm) for better presentation and easy to be compared to the ground truth which is present in mm. For this analysis, the spatial resolution of this imaging tool is 0.25.

IV. Result Analysis

In this research, wavelet transform has been used to perform the image denoising and based on the wavelet coefficient; a wavelet-based thresholding method is applied to extract all the edges. Aortic annulus in ultrasound image presents as a white region corresponding to the human tissue. Therefore, the ROI is the white region which corresponds to the features in this image data. However, as the ultrasound image often suffers from speckle noise, this obstructs the segmentation process. To overcome this limitation, image size has been reduced. This results in fast computation time as well as reduction of the non-ROI area that may avoid the false features detection.

Other parameter which needs to take into consideration is the type of mother wavelet used. Haar wavelet is the simplest form of mother wavelet and easy to implement. However, it has a squared-shape function that is not suitable to be used as the topology of ROI consisting of several curve edges. Therefore, the Daubechies mother wavelet is the most suitable type of wavelet as it perfectly works in preserving all of the edges. Besides, high level of decomposition results in loss of information and distortion of the features while low level of decomposition may introduce ineffective noise filtration. Apart from that, hard thresholding is the best threshold method as it can still preserve the edges even though noise is not fully suppressed and vice versa.

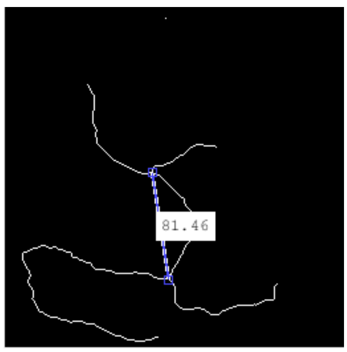

Fig. 9. Measurement of aortic annulus

In order to obtain the intersection points which indicates the distance of annulus, data is undergone several morphological operation starting with image binarization followed by image skeletonizing. In between this operation, the holes present in ROI should be filled in as it can cause the object to break apart. Next, number of iterations on shrink function should be assigned as n=20 in order to suppress the branches into point without distorting the ROI. In this process, Fig.9 shows the output of shrinkage function where the middle line which corresponds to aortic annulus is separating two regions; ascending aorta on the right and LVOT on the left. Once the automated measurement is done, data obtained is referred to Table I. in order to determine the exact size of new prosthetic valve offered by the manufacturer.

V. CONCLUSION

The aim of this research is to perform an automated measurement of annulus sizing as well as accurate measurement. This can decrease the workload of cardiologists before performing the TAVI procedures. The correct measurement of aortic annulus size is important as the measurement is used for selecting the best size of prosthetic valve for TAVI patients. Inaccurate deployment of prosthetic valve would pose risks to the patients.

The application of wavelet thresholding method on echocardiogram causes the algorithm to suppress all the unwanted signal and smoothen the image. Based on the results, the final measurement of aortic annulus is successfully obtained automatically. From the analysis, the crucial part of this research is in the pre-processing stage which requires image denoising steps to determine the accuracy of the measurement of the annulus size. Final measurement of annulus is then compared with the ground truth value which has been obtained from the manual marking performed by the experts. Therefore, this proposed framework has given promising output as the size of aortic annulus measured has the difference of only 0.1 mm with the ground truth.

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