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Digital Image Processing for Determining the Speed of Blood Flow in the Heart Based on the Doppler Effect

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ABSTRACT

A research study was conducted to estimate and visualize 2D vectors of blood flow in the heart using image processing algorithms to determine Doppler velocity at each point. The study used secondary data from ten patients who provided informed consent, encompassing healthy and unhealthy hearts. ECD image data were collected using a Philips epiq 7C machine in DICOM format. The image processing tasks, including area segmentation, flow velocity analysis, and area smoothing, were carried out using MATLAB R2016b software. These processes aimed to eliminate noise and other disturbances, enhancing the accuracy of blood flow velocity estimation in the heart. The study's findings included estimations and 2D vector visualizations representing the average blood flow velocity at each point within the heart. These achievements were made possible using image processing techniques to correct the acquired images, ensuring precise measurement of blood flow speed. Among the collected data, one patient exhibited indications of a healthy heart, with an average blood flow velocity of 40.2513 cm/s, a maximum speed of 68.5807 cm/s, and a minimum speed of 33.6971 cm/s. Deviations from the normal range of blood flow speeds were considered as potential abnormalities in heart health.

1. INTRODUCTION

The heart's critical function of circulating blood is well acknowledged, yet its diseases are the foremost cause of mortality worldwide, transcending economic disparities (Purwanti et al., 2013). The invisibility of cardiac abnormalities to the unaided eye complicates their detection. Contributing factors span from internal metabolic, innervation, and ischemic conditions to external lifestyle and physical influences (Aniamarta et al., 2022). The World Health Organization highlighted that in 2020, cardiovascular complications accounted for 16% of global fatalities over the last 19 years, out of a total of 55.4 million deaths (Willyono et al., 2018). West Sumatra reports a high incidence of these diseases, reflecting an urgent need for enhanced diagnostic strategies.

Ultrasonography stands out as a pivotal imaging modality that employs high-frequency ultrasonic waves to generate visual insights into the body's interior (Sugandi, 2018). Specifically, frequencies ranging from 1 MHz to 5 MHz, with a safe ultrasonic power of 0.01 W/cm^2, have become the standard for diagnostic evaluations (Gabriel, 1996). Initial adoption of ultrasound for internal organ assessment pre-1972 involved 2D real-time imaging; however, this method was limited to morphological observations, such as tissue shapes, without providing data on blood flow or vascular anomalies (Mulyani et al., 2012). Recognizing blood flow is critical to comprehending heart functionality and predicting disease trajectories (Harahap, 2013).

Doppler Echocardiography (ECD) has emerged as an indispensable technique for assessing blood flow and yielding crucial morphological and functional heart insights. This non-invasive, safe, and cost-effective method delivers superior images and stands as the favored modality for cardiac assessments (Oktamuliani et al., 2018b). ECD quantifies basal flow in the left ventricle, the heart's main pump for oxygen-rich blood, by capturing frequency shifts in the ultrasound reflections from circulating red blood cells. The resulting visual, a composite of Color Doppler and B-mode grayscale imagery, enhances diagnostic capabilities. This Color Doppler feature differentiates flow directionality, depicting inflow towards the transducer in warm tones and outflow in cool hues.

Despite its diagnostic prowess, ECD's performance is impeded by signal ambiguity due to the reflective nature of ultrasonic waves, which can generate misleading high-intensity data known as aliasing (Oktamuliani et al., 2018a). Aliasing distorts the velocity information of blood flow, presenting a significant challenge to achieving accurate diagnostics. It is imperative that sophisticated image analysis accompanies the acquisition of high-quality images to mitigate such errors (Sparzinanda & Nehru, 2017). While aliasing correction methods can refine the Color Doppler signal, they may inadvertently diminish the data essential for analyzing the dynamics of blood flow.

This study leverages the evolution of computational techniques to transcend these limitations by creating an image processing program in MATLAB R2016b. This innovation aims to refine the diagnosis of cardiac anomalies by meticulously analyzing ECD images. By harnessing the Doppler effect, the program discerns blood flow within organs and gauges the efficacy of blood vessel perfusion. The output images are rendered in nuanced color gradients, each hue corresponding to distinct velocity readings at specific pixel points. The algorithm enables the color map to visualize data, thereby facilitating the estimation and graphical depiction of the two-dimensional vector of blood flow velocity throughout the heart. This approach represents a stride forward in cardiac diagnostics, merging technological sophistication with clinical insight to enhance the clarity and reliability of echocardiographic assessments.

2. MATERIALS AND METHOD

2.1 Materials

The research samples were collected using Doppler echocardigraphy mechine. Satellite laptop of type L745 Core^{TM} i5 and MATLAB R2016b software were used to process images obtained from the Echocardiography Doppler tool. Image enhancement is one of the processes in image processing aimed at improving the quality of ECD images through image manipulation. This study was conducted to determine the estimation and 2D vector visualization of blood flow in the heart by determining the Doppler velocity at each point through the development of an image processing algorithm.

2.2 Image Acquisition

The image is recorded by USG Philips Epiq 7C and processed by a computer program as a digital image. Digital images can be considered discrete representations of data with spatial information (layout) and color intensity. A digital image consists of a number of elements called pixels, each of which has an intensity value of 1 (m:n). The index m and n determine the location of the row and column of the image, respectively. The ECD data recorded by the Philips Epiq 7C ultrasound was provided from the heart poly at Andalas University Hospital in video form. The results were obtained as data for all patients who have performed an ECD examination at the Andalas University Hospital. The ECD reads the Philips Epiq 7C image in DICOM format (Digital Imaging and Communications in Medicine), the standard used to store, print, and transmit medical record results from medical devices in .dcm format.

2.3 Image Pre-Processing

During the image pre-processing stage, a total of 7.69 GB of DICOM videos data were obtained from the ECD acquisition of ten patients. Informed consent from all patients was obtained to participate in this study. Out of these videos, only eight videos were found suitable for this study, with each video representing a patient who had been referred by a cardiologist at Andalas University Hospital. The videos were read and processed offline using the microDICOM viewer computer program, which produced a 2D digital images in BMP (Basic bitmap picture) format. The image yielded a spatial resolution of 24 bits for RGB color and a 2D grid of 800x600 pixels. When multiple images were grouped together for a specific purpose, each image was referred to as a frame, and an entire series of frames was referred to as a multi-frame image.

2.4 Image Processing

Image processing is the procedure of processing pixels in a digital image for a specific purpose. The purpose of image processing is to rectify errors in the image signal data which arise due to transmission and acquisition. The image processing stages include segmentation, dealiasing, and smoothing. The ECD images from healthy and unhealthy patients obtained from healthy and unhealthy patients have an image size of 0.333 mm or 827.716 pixels. A bitmap of 15 cm with a resolution of 24 bits is used to display and save the images in BMP format (.bmp).

3. RESULTS AND DISCUSSION

Data from patients with both healthy and unhealthy heart conditions were collected at Andalas University Hospital. The collected data underwent filtering based on criteria such as good image quality and a clear view of heart chambers. The number of frames within each video was considered, as a higher number of frames correlated with improved image quality and clarity. The analysis of the data involved segmentation, dealiasing with blood flow velocity, and smoothing of the identified areas. The processing of the data was performed using MATLAB R2016b software.

3.1 Transport results and Image Selection

ECD imaging was conducted on ten patients; however, only eight medical records were deemed usable, while two data sets were damaged. The damage is evident from the poor image quality, variations in the appearance of heart chambers, and grayscale images. For the study, 74.6 MB of raw data, consisting of eight videos, was utilized. The selection of these specific videos was based on their ability to accurately depict the heart's movement, size, and shape. The DICOM videos were converted offline into 2D images using the MicroDicom application.

Table 1 The result data is the number of frame transport videos.

No	Patient Code	Video Length (seconds)	Number of Frames
1	A	3	46
2	B	2	35
3	C	1	21
4	D	3	48
5	E	2	39
6	F	3	42
7	G	2	39
8	H	2	40

Table 1 provides an overview of the video conversion process, where videos are transformed into multiple frames. The duration of each video may vary, resulting in a different number of frames being generated. A higher number of frames in each video corresponds to improved quality and clarity of the captured images. This is because the motion of objects in the video is captured more accurately without disruptions. Specifically, the selected images from frames with high image quality and a clear depiction of the apical-3 chamber's shape are chosen for further processing. These images highlight the left ventricle, left atrium, and aorta within the heart chambers. The number of frames represents the sequential movement captured in the video.

3.2 Results of Segmentation Image of Area Blood Flow

Figure 1 displays the data obtained from the segmentation process, and the corresponding output for patient A. Image segmentation generates a binary image (Figure 1(b)), assuming two distinct possible values. The segmentation technique utilizes a thresholding method, transforming the resulting grayscale image with 8 bits (having a grayscale degree of 255) into a binary image consisting of only black and white pixels. In this binary representation, valid pixel values are assigned as 1 for the object (depicted as white) and 0 for the background (to be removed, represented as black).

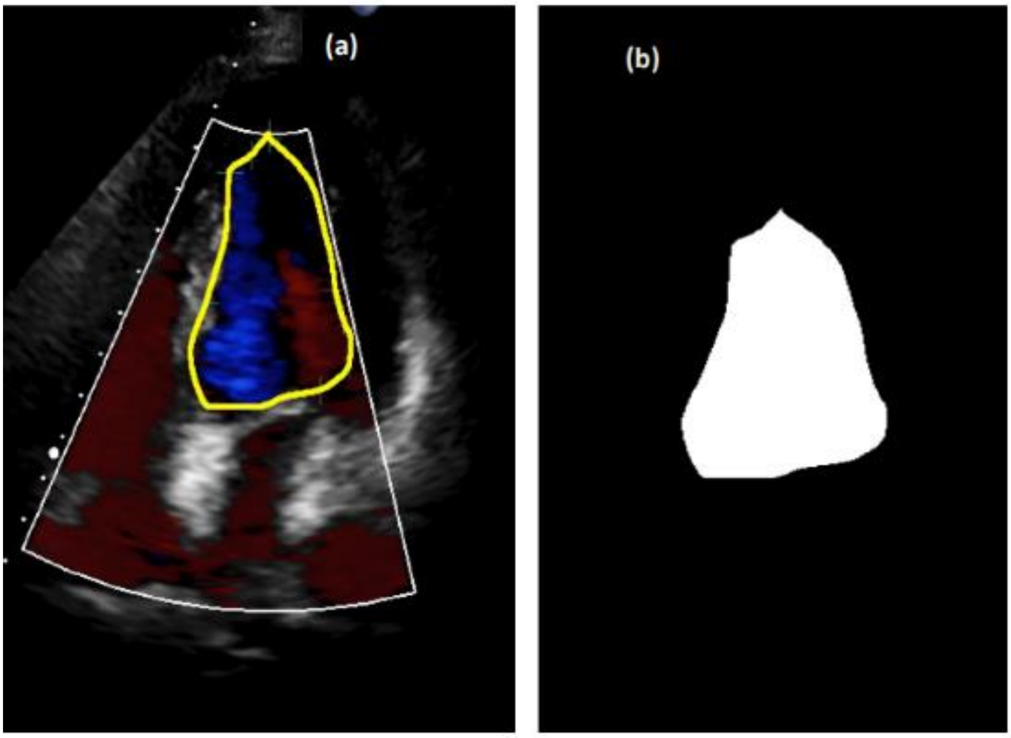

Figure 1 Image segmentation on patient A's LV blood flow (a) an original ECD image of ROI selection process, and (b) binary image of blood flow area boundary.

The segmentation process focuses on identifying the boundary of the left ventricle (LV) by analyzing the blood flow area. The region of interest (ROI) is selected by clicking on the image and choosing a starting point within the object's boundary, as shown in Figure 1(a). The resulting output image adjusts the brightness level based on the specified threshold value (T). The threshold value ranges from 0 to 255, with values closer to either extreme, making it more challenging to distinguish the object from the background. If the intensity value of a pixel exceeds or is equal to the threshold value, it is represented as white in the output image. Conversely, if the intensity value is lower than the threshold value, the resulting pixel in the image is black.

3.3 Results of Dealiasing and Smoothing Image

Figure 2(a) illustrates the outcomes of dealiasing the blood flow velocity. The speed of blood flow is represented on a scale in Nyquist speed and its direction. Dealiasing extends the Nyquist speed range and resolves the ambiguity in the direction of blood flow caused by aliasing. Figure 2(a) is analyzed to identify the positions of signal ambiguity in the red and blue Doppler velocity planes. The red indicates the recovery of negative error ambiguity toward the correct negative speed. In contrast, blue signifies the recovery of negative error ambiguity toward the correct positive speed.

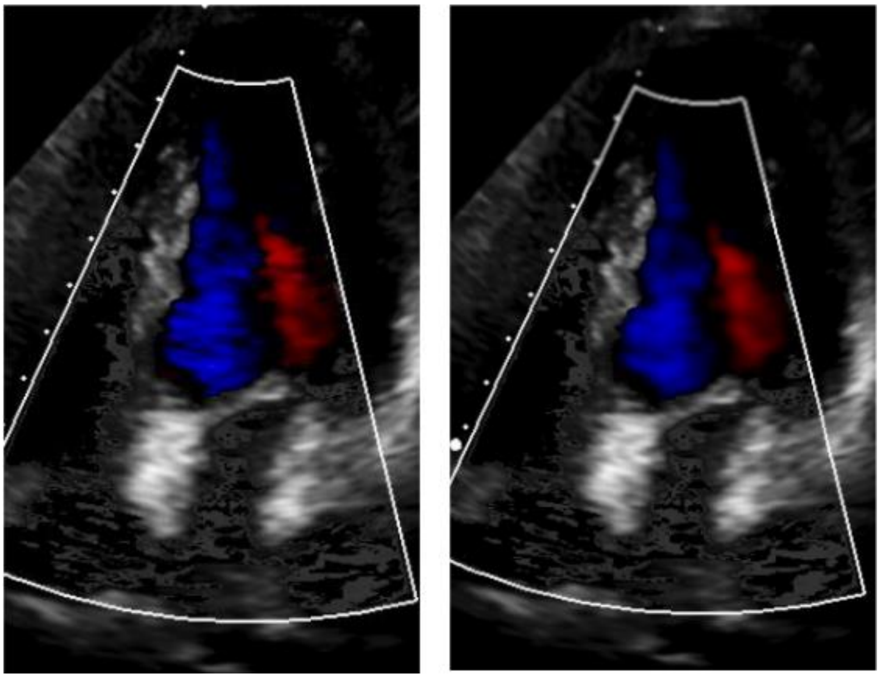

Figure 2 ECD image of patient's LV blood flow (a) image after the dealiasing process, (b) color Doppler smoothing area image.

Figure 2(b) showcases the results of image smoothing in patient A. The noise in the ECD image is eliminated through image filtering. Moreover, the image edges appear sharp, resulting in a smoother effect on the blood flow object. Typically, noise arises due to poor image acquisition during the data acquisition or transfer. Removing noise is essential to obtain accurate speed measurements. Each pixel is examined sequentially to detect and process images containing noise, starting from the initial to the final pixel. Consequently, larger image sizes entail more pixels to be processed.

3.4 Determination of Vectors and Velocity of Blood Flow

Visualization of blood flow with circulating velocity in space and time provides valuable diagnostic and prognostic information regarding cardiovascular disorders. Blood dynamics involves the study of fluids in motion, specifically focusing on their velocity. The velocity vector represents the change in position over time, effectively indicating the speed at which blood flows within the left ventricle (LV). By assessing the velocity at various points along the transducer beam, one can determine the direction and speed of blood flow, which is essential for obtaining accurate information on the circulating velocity vector at each point. The position of the transducer is crucial in getting the desired beam angle.

Figure 3 illustrates the utilization of different colors to display the blood flow velocity of patient A. In the ECD image, each color corresponds to a specific velocity and flow direction within a particular area, representing the average velocity in that region. Red indicates flow towards the transducer, while blue represents flow away from the transducer. Using ECD, estimating and visualizing a two-dimensional (2D) blood flow velocity vector within the LV is possible.

In the 2D vector representation of patient A's blood flow velocity, as depicted in Figure 3, the measured speed was 33.6971 cm/s using a frame rate of 16 Hz. This estimation is based on observing a specific color during a 2-times zoom-in image observation cycle, where each color represents a distinct 2D directional vector. The blood velocity is calculated using the Doppler principle, which involves measuring the speed of ultrasonic waves in two situations: when they encounter moving blood cells and when the echo is reflected by the moving blood cells.

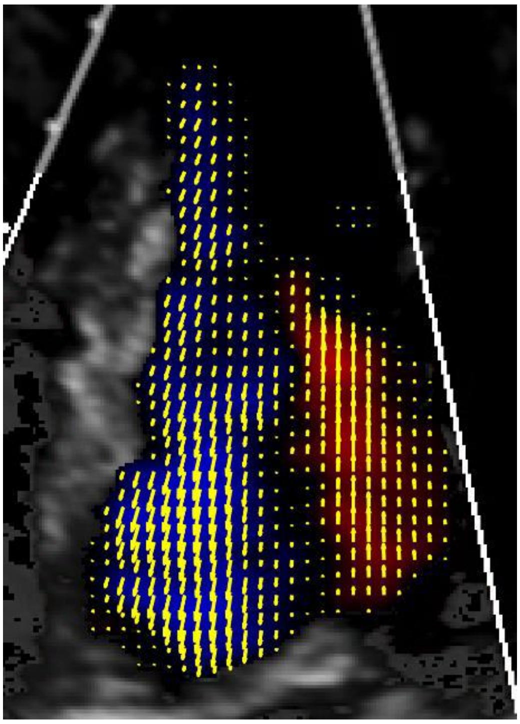

Figure 3 2D velocity vector on LV of patient A (zoom-in 2x).

Table 2 Blood flow velocity reading data.

No	Patient Code	Average of Velocity (cm/s)	Frame rate (Hz)
1	A	33.6971	16
2	B	51.3860	18
3	C	56.7447	24
4	D	46.0200	15
5	E	58.9008	17
6	F	68.5807	17
7	G	40.2513	17
8	H	39.7592	15

According to Oktamuliani et al. (2018a), the blood flow rate of a healthy heart is approximately 40 cm/s. Without constriction or blood resistance within blood vessels, blood flows normally (Harun et al., 2016). Table 2 displays the normal blood flow velocities results, where patient code G exhibited a speed of 40.2513 cm/s, indicating a healthy heart. The highest velocity was recorded in patient code H, while the lowest was observed in patient code A. The normal blood flow velocity was obtained after applying image processing techniques using Matlab R2016b software. Through image processing, the image was corrected to accurately measure the speed of blood flow, enabling estimation and visualization. The peak blood flow rate is typically found in the inferior vena cava. Any deviations from normal speeds indicate abnormalities in the heart. It is worth noting that the input frequency given through the transducer was 2.5 MHz, which is within the transducer's specifications (3.5 MHz) and does not exceed it.

4. CONCLUSION

The deployment of image processing to refine Echo Color Doppler (ECD) images has successfully mitigated the challenges of velocity overestimation inherent in cardiac diagnostics. By employing dealiasing and smoothing algorithms, the veracity of blood flow velocities was restored, augmenting the precision of cardiovascular assessments. Data analysis revealed one subject manifesting normal cardiac function with an average blood flow velocity of 40.2513 cm/s. Recorded velocities spanned from a high of 68.5807 cm/s to a low of 33.6971 cm/s. Variations from this established normative range are indicative of potential cardiac irregularities, warranting further investigation. This study's findings underscore the efficacy of advanced image processing in enhancing the diagnostic capabilities of ECD, thereby contributing to more reliable detection of heart conditions.

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