Automated Fetal Cardiac Valve Movement Detection for Modified Myocardial Performance Index Calculation

Jingjing Wang, *IEEE Student Member*, Amanda Henry, Alec W. Welsh,
Stephen J. Redmond, *IEEE Senior Member*

***Abstract*—The Modified Myocardial Performance Index (Mod-MPI) is becoming an important index in fetal cardiac function evaluation. However, the current method for Mod-MPI calculation can be time-consuming and demonstrates poor inter-operator repeatability. This paper presents an automated method for detecting the opening and closing events of fetal cardiac valves with the aim of automating the Mod-MPI calculation. Fifty-four Doppler ultrasound images, showing blood inflow and outflow for the left ventricle, are analyzed to attempt to automatically detect the timings of a total of 905 opening and closing events for both aortic and mitral valves. Timings are found according to the morphological characteristics of waveforms as well as intensity information of images. The proposed method can detect the four valve movement events with high sensitivity (95.60-98.64%) and precision (96.85-100.00%). Results are verified by comparison with manual annotation of same images from an expert.**

I. Introduction

The myocardial performance index (MPI), defined as the sum of isovolumetric contraction time (ICT) and isovolumetric relaxation time (IRT) divided by ejection time (ET), was first introduced by Tei *et al.* for adult cardiac evaluation [1]. Over the past five to ten years, MPI has been shown to correlate well with other measures of global left ventricular performance [2-4]. Tsutsumi *et al.* first utilized MPI to assess left and right myocardial function in fetuses [5].

Friedman *et al.* first proposed to acquire the left fetal ventricular MPI using one Doppler waveform to reduce the effect of fetal heart variations, such as variations in heart rate and ventricular geometry [6]. Later, use of the opening and closing clicks of the aortic valve were proposed as fiducial points in the waveform when calculating the MPI, as this would improve the estimation of the ET interval [7]. Hernandez-Andrade *et al.* introduced the modified MPI (Mod-MPI) for the left ventricle, using the beginning of opening and closing Doppler echoes of the mitral and aortic valves to define the three time periods required for MPI calculation, with improved repeatability [8]. Despite those improvements, as the current method for MPI calculation is based on manual annotation, there is still a broad variation in normal ranges of Mod-MPI [5-7, 9-11], due to lack of consensus and observer errors.

An automated method for detecting valve movement timings is proposed in this paper. This method utilizes morphological characteristics of aortic and mitral flow in the Doppler ultrasound waveform to create four composite signals, from which the valve opening and closing events are identified. Intensity information from the Doppler ultrasound image is then combined with those composite signals to locate cardiac valve events.

II. Methods

A. Data

A total of 54 Doppler ultrasound waveform images were analyzed in this study. Images are obtained by the School of Women's and Children's Health, the University of New South Wales (UNSW), and the study was approved by the regional committee for research ethics (HREC ref 13/320). All recordings were obtained as described by Hernandez-Andrade *et al.*, with the Doppler sample volume placed on the lateral wall of the ascending aorta, below the aortic valve and just above the mitral valve, which enables recording movement of both valves simultaneously [8]. A Voluson e8 Expert ultrasound machine, with settings as suggested by Meriki *et al.* [11], was used for images acquisition and storage.

B. Data Preprocessing

The raw Doppler waveform data was stored in a raw image format and subsequently converted to hierarchical data format (HDF version 5) using the HDFView Java GUI. The Doppler waveform data extracted from HDF5 file, shown as Fig. 1(a), is then analyzed using the MATLAB programming environment.

Using MATLAB, the contrast of raw image is first enhanced by mapping intensity values in the image to new values so that the bottom 1% and top 1% of raw image intensities are saturated to 0 and 1 respectively. The image data is then median filtered to remove noise, using a square five pixel by five pixel window. Envelope signals and cumulative intensity signals are constructed from the image to assist in locating the various valve events. The upper waveform envelope corresponding to aortic flow, shown in the upper half of Fig. 1(b), is constructed by finding the largest pixel y-coordinate from all pixels for each vertical line whose intensities are larger than a threshold. The threshold for each image is determined using balanced histogram thresholding [12], which gives the optimum threshold that divides the image histogram into background and foreground. Similarly, the lower envelope, corresponding to mitral flow (bottom half of Fig. 1(b)), is calculated using the minimum pixel coordinate along each vertical for all pixels on the line with an intensity value greater than the set threshold.

Cumulative intensity signals are obtained simply by summing pixel intensities in upper and lower halves of each vertical line for aortic and mitral flows, respectively.

J. Wang and S. J. Redmond are with the Graduate School of Biomedical Engineering, UNSW Australia. (e-mail: jingjing.wang@student.unsw.edu.au; s.redmond@unsw.edu.au)

A. Henry and A. Welsh are with School of Women's and Children's Health, UNSW Australia. (e-mail: amanda.henry@unsw.edu.au; alec.welsh@unsw.edu.au)

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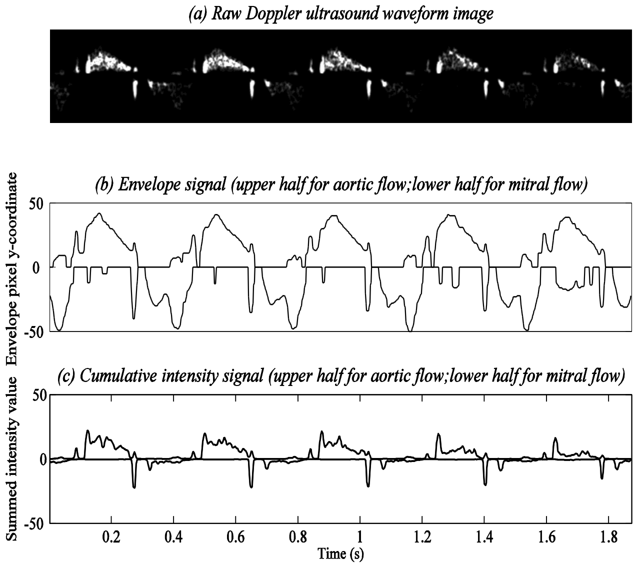

Fig 1. (a) Raw Doppler waveform image, the horizontal axis represents time and vertical axis repersents velocity. (b) Envelope signal constructed from the waveform image. Upper half and lower half correspond to aortic and mitral flows, respectively. (c) Cumulative intensity signal.

For simplicity, aortic and mitral waveform envelope signals are denoted as a_e and m_e, whilst intensity signals for aortic and mitral flow are denoted as a_i and m_i.

C. Composite signal construction

The general idea of the method is to find valve timings according to morphological characteristics of aortic and mitral flow. Four composite signals are constructed from the cumulative intensity and envelope signals to locate the four valve events.

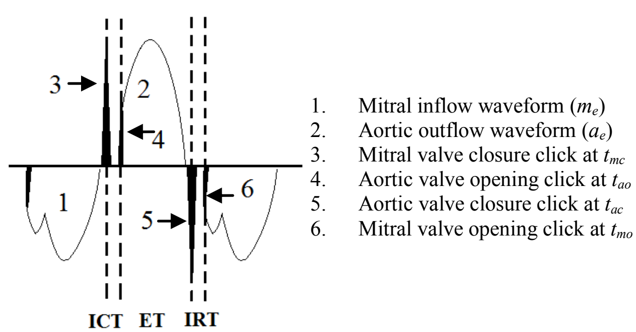

Fig 2. Schematic representation of flows and valve clicks [13].

1) Mitral valve closure, t_{mc}: The composite signal for detecting mitral valve closure is constructed using envelope signals a_e and m_e. As shown in Fig. 2, in envelope signal a_e, when a mitral valve closure click happens at t_{mc}, it is followed by aortic outflow waveform, and the magnitude of a_e in the preceding epoch is small. Meanwhile in m_e, after t_{mc} the magnitude of m_e becomes small, as the mitral valve has closed and mitral flow has stopped.

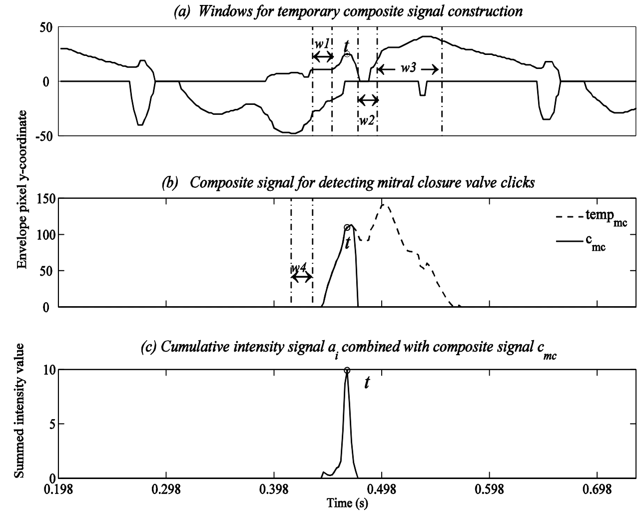

Fig 3. (a) Time windows of example point t. In w_1 ($t - 0.03$s to $t - 0.012$s) the magnitude of envolope signal of aortic flow a_e is small whereas the magnitude of a_e is large in w_3 (t +0.05s to t + 0.09s); the magnitude of m_e is small in w_2 (t + 0.012s to t + 0.03s). (b) w_4 ($t - 0.05$s to $t - 0.03$s) is chosen and $temp_{mc}$ is constructed using equation (1); c_{mc} is obtained using equation (2); (c) Cumulative intensity signal a_i combined with composite signal c_{mc}, denoted as $\hat{a}_i$

For each time point, t, in a_e, a time window before t and two time windows after t are chosen, denoted as w_1, w_2 and w_3, respectively, shown as Fig. 3(a). A temporary signal is calculated and then further processed using the following equations to obtain the composite signal, c_{mc}:

$$temp_{mc}[n] = a_e[n] - m_e[n] + 4E_{w3}\{a_e\} - 2E_{w1}\{a_e\} - 2E_{w2}\{m_e\} - 2E_{w1}\{m_e\} - 4E_{w3}\{m_e\}, \quad (1)$$

$$c_{mc}[n] = temp_{mc}[n] - 6\max_{w4}\{temp_{mc}\}, \quad (2)$$

where $E_{wx}\{signal\}$ is mean of values within time window w_x in certain signal. To locate mitral valve closure clicks, the intensity signal a_i is then combined with c_{mc} as follows:

$$\hat{a}_i[n] = \begin{cases} 0 & \text{if } c_{mc}[n] = 0; \\ a_i & \text{otherwise.} \end{cases} \quad (3)$$

This combined signal, shown in Fig. 3(c), can be used to find mitral closure clicks by searching the local peaks which occur when the height difference between a peak and trough is less than certain threshold, which in this case is set as half of the median value of the non-zero values in $\hat{a}_i$.

Similar schemes are implemented for the remaining three valve clicks.

2) Aortic valve opening, t_{ao}: To construct composite signal c_{ao} for aortic opening detection, a new window w_5 is defined, shown as Fig. 4. c_{ao} is obtained using following equations:

$$temp_{ao}[n] = a_e[n] - m_e[n] + E_{w5}\{a_e\} - E_{w4}\{m_e\},$$
$$c_{ao}[n] = temp_{ao}[n] - 2\,E_{w4}\{temp_{ao}\} - E_{w4}\{m_e\} - E_{w1}\{m_e\}.$$

Similar to equation (3), the composite signal is combined with the intensity signal to find aortic valve opening clicks. The same windows, w_4 and w_5, are used to obtain composite signals for aortic closure and mitral opening valve clicks.

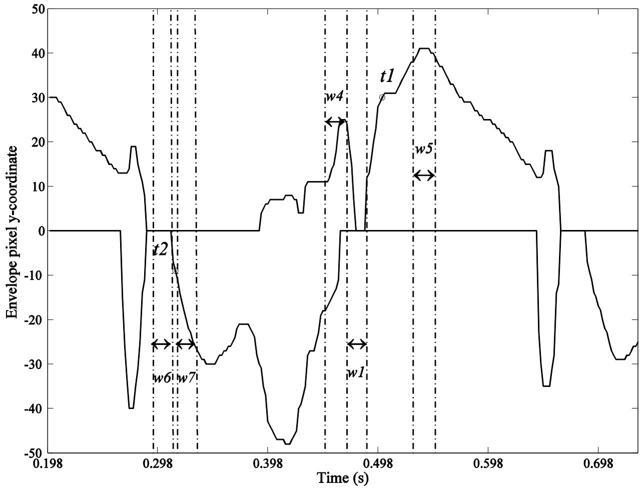

Fig 4. Windows for composite signals c_{ao} c_{ac} and c_{mo} constuction. w_4 (t_i − 0.05s to t_i − 0.03s), w_5 (t_i + 0.03s to t_i + 0.05s) and w_1 (t_i − 0.03s to t_i − 0.012s) shown here are drawn based on t_1 whereas w_6 (t_i − 0.02s to t_i − 0.002s) and w_7 (t_i + 0.002s to t_i + 0.02s) are drawn based on t_2. Both w_4 and w_5 are used for constructing c_{ao} c_{ac} and c_{mo}. w_1 is used for obtaining aortic valve opening composite signal c_{ao}; w_6 and w_7 are used for obtaining c_{mo}.

3) Aortic valve closure, t_{ac}:

$$temp1_{ac}[n] = m_e[n] - E_{w4}\{m_e\} - E_{w5}\{m_e\} - E_{w5}\{a_e\},$$
$$temp2_{ac}[n] = m_e[n] + 2E_{w4}\{a_e\} - 4E_{w5}\{a_e\} - 2E_{w4}\{m_e\},$$
$$c_{ac}[n] = temp1_{ac}[n] \cdot temp2_{ac}[n].$$

4) Mitral valve opening, t_{mo}: Another two windows w_6 and w_7 are used for c_{mo}, shown in Fig. 4.

$$temp1_{mo}[n] = m_e[n] + E_{w5}\{m_e\} + E_{w6}\{m_e\} - 4E_{w4}\{m_e\} - E_{w1}\{m_e\} - 4E_{w4}\{a_e\} - 2E_{w7}\{a_e\},$$
$$temp2_{mo}[n] = m_i[n] - E_{w4}\{m_i\},$$
$$c_{mo}[n] = temp1_{mo}[n] \cdot temp2_{mo}[n].$$

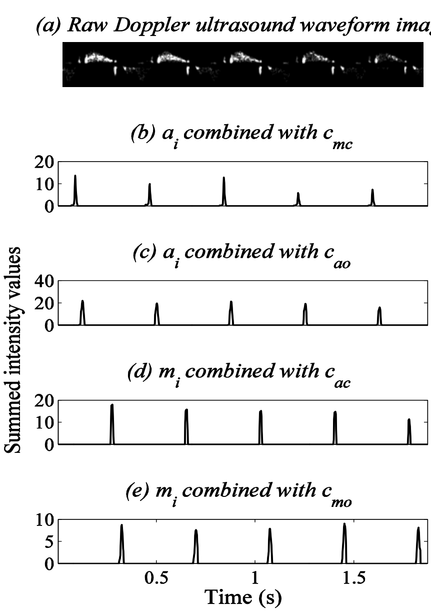

Fig 5. (a) Raw Doppler waveform image; the horizontal axis represents time and vertical axis represents velocity. (b) Composite signal c_{mc} combined with envelope signal a_i for locating mitral valve clousre click. (c) Composite signal c_{ao} combined with a_i for aortic valve opening detection. (d) Composite signal c_{ac} combined with m_i for mitral valve closure detection. (e) Composite signal c_{mo} combined with m_i for mitral valve opening detection.

Fig. 5 shows the combined signals of composite signals and corresponding cumulative intensity signals. By searching local peaks in those four signals, mitral closure, aortic opening, aortic closure and mitral opening clicks can be located.

III. Results

To evaluate the performance results, the test images are annotated by an expert ultrasonographer from the School of Women's and Children's Health, at UNSW. The manual annotation valve events in each image are used as a gold standard for comparison. An error tolerance of ±4 ms (±2 pixels in the image, limited by the machine) is used when determining if a valve event matches the expert's annotation.

Table I shows the detection results for each of the four valve movement events. For each valve movement, true positive gives the number of correct detections; false positive is the number of wrongly detected events; false negative represents missed valve events. Precision and sensitivity are calculated as:

Precision=True positive/(True positive + False positive)

Sensitivity=True positive/(True positive + False negative)

TABLE I. Precision and sensitivity results for the proposed automated detection algorithm for four valve click event over 54 images.

	Number of Detected Valve Clicks			
	Mitral closure	***Aortic opening***	***Aortic closure***	***Mitral opening***
True positive	218	216	216	227
False positive	5	7	0	5
False negative	3	9	9	7
Precision (%)	97.76	96.85	100.00	97.84
Sensitivity (%)	98.64	95.60	96.00	97.01

TABLE II. Mean and standard deviation of Mod-MPI for manual annotation and automated detection.

Method	**Mod MPI (Mean ± SD)**
Manual	0.49 ± 0.05
Automated	0.51 ± 0.06

IV. Discussion and Conclusion

The current most common method for MPI calculation is through manually annotating the cardiac valve timings on Doppler ultrasound waveform image, which can be time-consuming and requires expertise. Another issue facing the adoption of MPI indicators of fetal heart function is intra- and inter-observer differences. So far the highest intra- and inter-observer correlation coefficient (ICC) for left Mod-MPI calculated using manual annotation results is 0.930 and 0.857 [14]. The automated method proposed in this paper is faster than manual annotating and no expertise is required when using this method; however, expertise is required to obtain the correct waveform for analysis, showing simultaneous flow through both aortic and mitral valves. Moreover, the algorithm always gives same detection results for an image.

It can be seen from the result that both mitral and aortic valve closure detections are performed with high precision. This is mainly due to the fact that mitral and aortic valve closures tend to form clearer and more distinguishable clicks on the image. All detected aortic closure events are correct however 9 events could not be identified. The reason is that events are detected based on searching the intensity signal, therefore if other clicks for the same event are much brighter than another click (that is bright enough to be observed by human), it can be missed during the searching process. This implies some improvements could be made by backtracking to find apparently missed events, using a reduced threshold for these less bright valve clicks.

Table II shows that the automated slightly over estimates the Mod-MPI compared to the human observer. However, as Mod-MPI is a highly sensitive index due to its definition, a 2 ms (1 pixel) difference in time interval, IRT for example, will leads to a variation in the Mod-MPI as large as 0.02, assuming normal ICT and IRT values [15]. Left Mod-MPI values reported in the literature vary from 0.22 to 0.66, according to Meriki *et al.* [11]. Therefore the result of this automated method is still acceptable in comparison to inter-human variability. It should also be noted that the gold standard in this study was obtained from only a single human expert, which is also expected to suffer from the same variability described above.

Comparing to other reports of cardiac valve event detection, Marzbanrad *et al.* used a Doppler ultrasound audio signal (DUS) and fetal electrocardiogram (fECG) to identify cardiac events, which requires simultaneously recording of the abdominal fECG and DUS [16]. The result shows a high percentage of correctly identified mitral opening and aortic closure events, 99.7% and 94.7%, respectively. However the sensitivities in identifying mitral closure and aortic opening events were only 82.5% and 89.1%.

The recent study by Lee *et al.* evaluated the reproducibility of left Mod-MPI using an automated system [17] developed by Samsung Electronics Co. Ltd, which can be applied to images that have very clear valve click events [14]. This system requires the selection of regions of interest (ROI) in the Doppler ultrasound waveform image, and finds events within the ROI. The results showed high inter- and intra- operator reproducibility, however ICC values for both inter- and intra-operator are not 1.0; one possible reason for this might be the selection of ROI could vary between operators.

The method presented in this paper utilizes the morphological characteristics of aortic and mitral flow of the Doppler ultrasound waveform image, making obtaining proper waveform images crucial. Full aortic and mitral flow waves, as well as minimal baseline interference, are expected by the algorithm. Despite all the technical refinements suggested by Meriki *et al.* [11], the Doppler ultrasound images obtained still vary in different aspects. The coefficients chosen to construct the composite signals are obtained empirically by observing images. Future work will apply regression techniques to optimize the process. Moreover, future study will focus on automatically selecting waveforms which are appropriate for analysis, as well as developing a more comprehensive method to deal with waveforms with different characteristics. This proposed algorithm promises a much more convenient and consistent way of calculating the Mod-MPI index, hence making fetal cardiac function evaluation based on Mod-MPI easier and more reliable.

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