Investigation of a Hierarchical Fuzzy Model for Echocardiographic Assessment of Trans-valvular Hemodynamic Indexes

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Abstract

The work presented in this paper is directed toward the automated analysis of Doppler trans-mitral diastolic inflow (MDI) and trans-aortic systolic outflow (ASO) using a hierarchical fuzzy inference system. The multi-stage system consists of two inference templates related to MDI and ASO respectively. The desired membership and rules for the fuzzy sub-systems in each template were generated according to the different flow pattern characteristics, which were estimated by the timing and morphological features of the ECG, converted Doppler backscatter power and flow velocity profiles. The performance of the system has been evaluated by comparing the quantification results with those obtained by expert manual analysis on a series of 180 in vivo continuous wave Doppler echocardiographic images. The results of the automated system correlated well with manual tracing (r>0.90 with at least 81% match rate). Overall. the system is effective, computationally efficient, and overcomes the problems of initialization and velocity profile modeling that were encountered in the literature.

1. Introduction

Spectral Doppler echocardiography has been accepted as the standard non-invasive diagnostic procedure for evaluating cardiac hemodynamics. However clinical ability to draw conclusions from derived parameters is still dependent on manual or semi-auto tracing of the flow patterns. It is time-consuming, labor-intensive and introduces unavoidable intra- and inter-observer variability. In the automatic analysis of trans-valvular blood flows, accurate estimating start and end timings of trans-mitral diastolic inflow (MDI) and trans-aortic systolic outflow (ASO) is the essential step to identify other hemodynamic parameters. Conceptually, MDI can simply be determined by tracing the trans-mitral velocity profile from the start of diastolic upstroke to the end of diastole; and ASO can be estimated by tracing the trans-aortic velocity profile from the start of systolic upstroke to the end of systole (see Figure 1). In practice, it is far from straightforward for a machine to perform the task that is so simple for a skilled ultrasonographer. The authors have developed an adaptive algorithm for identification of trans-valvular flow velocity profiles [1]. By far the major problem is how to determine the start and end timing of the trans-valvular flows with high acceptably accuracy using a computer-based system.

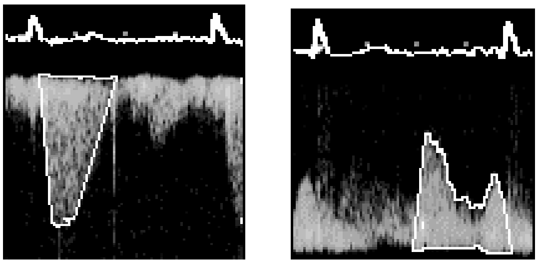


Figure 1. Envelopes of ASO (left) and MDI (right) waveforms

The nadirs located at both sides of a wave are the most common points used to locate the start and end points of the wave. Loupas and collegues [2] have identified the start of the systolic upstroke in Doppler spectrograms of the uterine arteries by means of the local curvature of the smoothed maximum frequency envelope. However this may not always give the correct answer for the Doppler spectrograms of trans-valvular blood flows. The Doppler trans-valvular spectrogram is a spectral display of velocity distribution usually resulting in a non-smooth velocity profile. The zigzag velocity profile and the presence of a non-standard definition waveform may make it difficult to locate the nadirs related to the start and end of the waveforms. And at the instant of mitral or aortic valve opening, trans-valvular flow is not laminar but turbulent which causes the Doppler velocity signals to emerge from a noisy baseline. In addition, the presence of valvular opening and closure clicks in the velocity trace may partially hide the apparent nadir points. All these problems that make the real nadir points difficult to identify have rightly caused the question: What does the ultrasonographer look for when visually detecting the start and end timings of trans-valvular flows in the spectrograms?

2. System Design

In practice an experienced ultrasonographer can adequately estimate the optimal starting and end points of the blood flow waveforms even with non-smooth velocity profiles by visual (qualitative) inspection in those difficult cases, such as lack of reliable presence of nadir points, valvular opening and closure spikes with varying amplitude and shape, or valvular cusp fluttering spikes. Expert ultra-sonographers make use not only of the shape of the velocity waveforms but also of the strength of signals and the temporal contextual information obtained from the ECG. We therefore have proposed an intuitive fuzzy rule-based system to emulate an expert ultrasonographer’s performance in determining the start and end timing of trans-valvular flows in CW Doppler echocardiographic images.

To avoid the “curse of dimensionality” which is one of the most important difficulties in dealing with fuzzy systems [3], the structure of the detection system developed adopts a hierarchical model as introduced by Raju and colleagues [4]. In this model, the total number of rules is only a linear function of system variable. Raju and colleagues suggest that only two variables should be chosen at each level, so it is easy to add or subtract one variable without altering other rules in the set. The interpretation of this structure is also close to human reasoning since the intermediate states are of significance in the study.

The overall system to be discussed can be divided into four stages of analysis as shown in Figure 2. First, the parameter extractor employs a mimetic approach to form parameter vectors for selected features including the ECG curve, the velocity profile, and the converted Doppler backscatter power curves [5] of the base spectrogram part (*bpc*). Second, a two-layer fuzzy system is used to analyze the candidate sampling points of input curves, verifying that they have the shape, strength and timing of valve opening and closure clicks. In this phase, considerable use of temporal contextual information present in the synchronous ECG aids both in the detection of valvular opening and closure spikes and in the rejection of valvular fluttering. In the third stage, the pattern classification is applied to the outputs obtained from the second stage. The system classifies the trans-valvular flows into different patterns according to the presence of valvular opening and closure spikes on the velocity trace and low velocity turbulence spikes on the power-weighted mean velocity trace of the low velocity spectrum. In the last phase, the start and end timings of MDIW and ASOW are finally determined using the particular rules for each pattern.

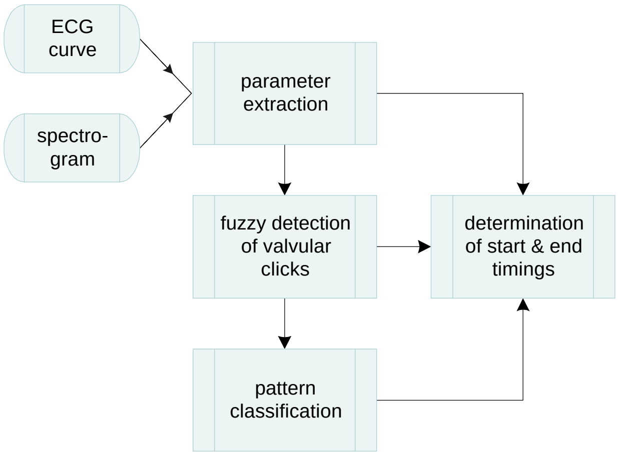


Figure 2. Determination of Start and End Timing of MDI & ASO

2.1 Parameter Extraction

Since lack of an existing standard, to use parameters is considered the most important when distinguishing spikes from non-spikes. The selected parameter are extracted from the given ECG and spectrogram for further valvular identification and pattern analysis of blood flow. The ECG parameter vector consists of nine locations of the main components of the given ECG. The 3-dimensional information of a spectrogram (time axis, velocity axis, and intensity axis) is extracted to form the parameter vectors of the spectrogram. The valvular opening and closure spikes registered on the velocity and converted Doppler backscatter power traces usually exhibit steep slopes, high amplitudes and small duration. Since the actual shape of the spikes and their relative timings are of diagnostic importance rather than their spectral composition, the detection system functions in the time domain by extracting parameters such as amplitude, slope, and timing.

2.2 Fuzzy Identification of Valvular Spikes

This section elaborates upon a new approach to identifying the valvular opening and closure spikes and low velocity turbulence spikes related to valvular movement. As shown in Figure 3, the fuzzy part of the system is designed to consist of two templates, T1 and T2. T1 is specifically configured for the analysis of trans-mitral inflow and T2 for trans-aortic outflow. Each template is made up of two layers of fuzzy subsystems, Layer A and Layer B.

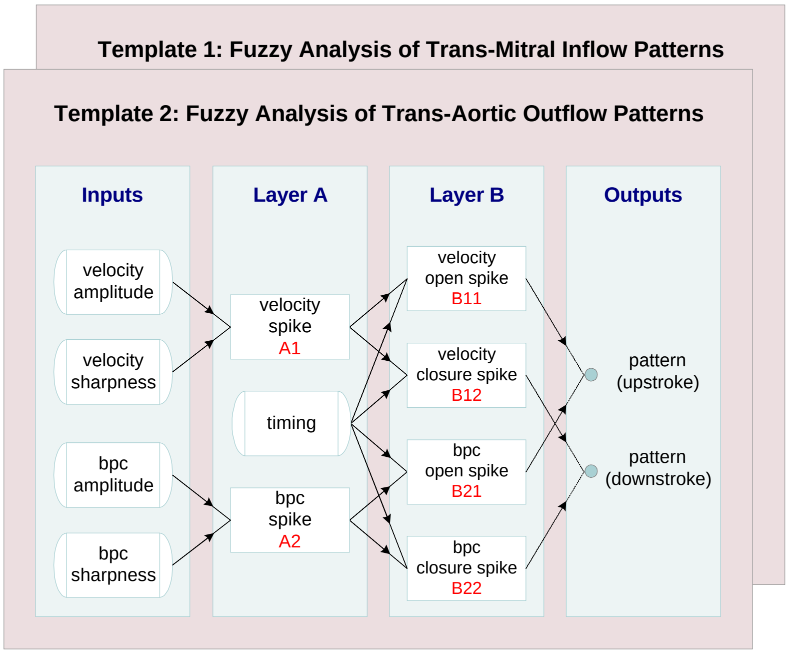


Figure 3. The hierarchical structure of the fuzzy system for spike identification and flow classification

The first layer, Layer A, consists of two Mamdani-type fuzzy inference subsystems establishing two measures of the likelihood. One is the degree of likelihood that a particular peak in the velocity profile is of the spike; the other one is the degree of likelihood that a particular peak of the spike in *bpc* trace. Layer A of Template1 has the same subsystem structure as it of Template2. The membership functions (MFs) associated with the fuzzy sets of the output variables in Layer A are implemented using the bell-shaped functions for smoothness and adaptability. The MFs associated with the fuzzy sets of the input variables are implemented using either one-sided or two-sided sigmoidal functions, since the sigmoidal MF is inherently open to the left or to the right which is appropriate for representing concepts such as "Very Low" or "Very High". The MF parameters of input variables are defined according to the corresponding statistical mimetic parameters.

The function of Layer B of the system is to determine the likelihood of the valvular opening/closure clicks and low velocity turbulence spikes related to valvular movements for the further classification of trans-valvular flow patterns. The valvular spike points are selected from the spike-likelihood outcomes of Layer A which hold all the possible spike candidates. The two characteristics determining how strongly a candidate peak/point tends towards being the true valvular spike are its likelihood of a spike and its timing. The maximum measures of likelihood of valvular spikes are used to classify the upstroke or/and downstroke parts of trans-valvular flow into a defined pattern.

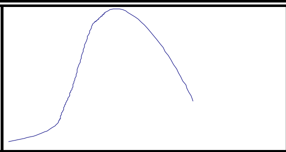
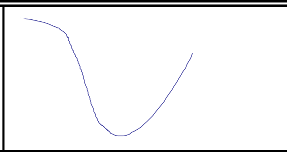
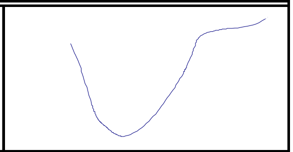
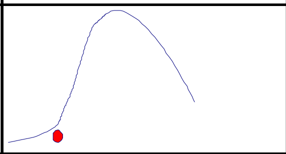
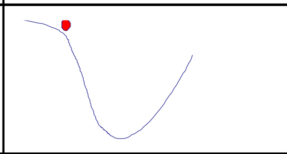
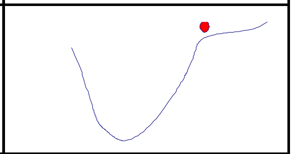
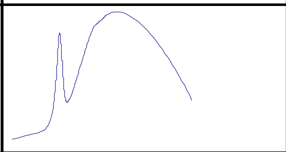
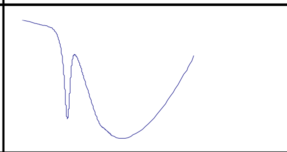
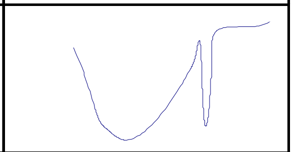
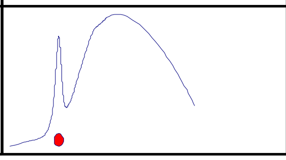
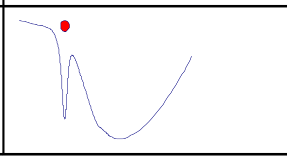
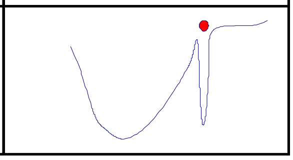
2.3 Trans-valvular Flow Pattern Classification

Following the identification of valvular spikes, the system classifies the trans-valvular flows into different patterns according to the presence of valvular opening or closure spikes in either the flow velocity trace or *bpc* traces or both. If a Layer B output (the valvular spike likelihood) of a particular spike candidate is greater than or equal to 0.75, that spike candidate will be defined as a mitral opening spike, aortic opening spike, or aortic closure spike. A summary of all possible flow patterns is given in Table 1. For example, if none aortic opening spike is detected in either the velocity trace or *bpc* trace, the trans-aortic systolic outflow will be classified as Pattern 1; if the aortic opening spike is detected in *bpc* trace but none in the velocity trace, the trans-aortic systolic outflow will be classified as Pattern 2, etc.

2.4 Determination of the Start and End of Flow

The start and end timings of trans-valvular flow are finally determined using the particular rules for each pattern. For example, if the upstroke of MDI is classified as Pattern 1, find the point with the minimum value in the velocity trace and the point with the minimum value in *bpc* trace before the peak of E wave in ECG (E_{peak}), compare the timings of these two points, and the start timing of MDI is defined at the point with the latter timing. If the upstroke of MDI is classified as Pattern 2, find the last negative peak points in the velocity and *bpc* traces and the points with minimum velocity and *bpc* value before the timing of the first detected aortic opening spike in *bpc* trace, compare the timings of these points, and the start timing of MDI is defined at the peak point with the latter timing. If the upstroke of MDI is classified as Pattern 3, find the last negative peak points in the velocity and *bpc* traces and the points with the minimum velocity and *bpc* value before the timing of the first detected aortic opening spike in the velocity trace, compare the timings of these points, and the start timing of MDI is defined at the peak point with the latter timing. If the upstroke of MDI is classified as Pattern 4, compare the timings of the first aortic opening spike in the velocity trace and the first aortic opening spike in *bpc* trace, define the interval for start point determination from the start of the trace to the spike with the earlier timing, find the last negative peak points in the velocity and *bpc* traces and the points with the minimum velocity and *bpc* value during the interval, compare the timings of these points, and the start timing of MDI is defined at the peak point with the latter timing.

Table 1. The summary of transvalvular flow patterns (● indicates the spike in the bpc trace)

No.	Trans-valvular Flow Patterns		
	trans-mitral diastolic inflow	trans-aortic systolic outflow	
	upstroke of E wave	upstroke of the flow	downstroke of the flow
1			
2			
3			
4			

3. Experimental Results

Since all images collected for the study are *in vivo*, there is no direct measurement can be obtained to validate the result. The performance of the automatic system is therefore evaluated by comparing the classification and quantification results with those obtained by expert manual analysis on the same test set.

Similar to those which are known to be epidemic in other areas of medical image analysis involving human judgement, inter- and intra-observer variability is unavoidable for the visual determination of the start and end timings and other significant timings of trans-valvular flows. Here the observer variability is analized within a panel of two observers who read studies from the same data set of 90 trans-mitral diastolic inflow images and 90 trans-aortic systolic outflow images. Each observer also performed the second readings more than two days after the first. Raw observations collected were: the start timing of flow, the end timing of flow, and the timings of the peak of E wave (*Epeak*) and the peak of A wave (*Apeak*) for the trans-mitral diastolic inflow or the timing of peak velocity (*Vpeak*) for the trans-aortic systolic outflow. Using the same procedure as in a clinical practice, the echo-cardiographic images were displayed in its original gray-color and the timing points of interest on each trans-valvular flow spectrum were picked by an experienced reader using a movable cursor on a computer screen. Each timing of interest is normalized by using the first R-wave peak point in the ECG of an echocardiographic image as the origin timing point.

Intra- and inter-observer variability are analyzed using correlation coefficients of measurements extracted in the different practices. Two intra-observer and two inter-observer correlations exist for each measurement which are shown in Table 2. The results show that better intra-observer correlations were obtained than inter-observer correlations and little intra- and inter-observer variability have been shown for *Apeak timing* and *end timing* of trans-mitral systolic inflows. This is probably because that the A wave of trans-mitral diastolic inflow lasts much less time than the E wave and the R wave in ECG provides an additional reference for identification and timing of the end of trans-mitral diastolic inflow. Due to the non-smooth clinical profile of trans-valvular flow and existance of flat velocity peaks, it is not surprise to obtain only fair but not good correlations for *Epeak timing* and *Vpeak timing*. The velocity spikes in some cases hiding the real velocity peaks also increase the difficulty to identify *Epeak timing* and *Vpeak timing*. In comparison, the start timing of MDI and the start and end timings of ASO are associated with higher variability as expected. It is important to note that for the developed computer-based analysis, intra- and inter-observer correlation is by definition one, since the automatic system gets the same answer every time it is provided the same input.

Table 2. Intra- & inter-observer correlations in the manual analysis of MDI and ASO

Observer Variability		Trans-mitral Diastolic Inflow				Trans-aortic Systolic Outflow		
		start	Epeak	Apeak	end	start	Vpeak	end
intra-observer	1_{st} observer	0.7208	0.8361	0.9932	0.9897	0.7965	0.8392	0.7299
	2_{nd} observer	0.7637	0.8964	0.9888	0.9910	0.8303	0.7975	0.7944
inter-observer	1_{st} reading	0.6921	0.8295	0.9869	0.9860	0.7842	0.7771	0.6505
	2_{nd} reading	0.7631	0.7470	0.9803	0.9883	0.7347	0.8149	0.7420

Table3.Comparison of significant timings of trans-valvular flows between manual reference and automatic results, in which the unit of each measures (except r) is pixel.

Measurements		Manual Reference		Automatic Results		Automatic vs. Manual Results			
		mean	SD	mean	SD	r	abs. difference mean	abs. difference max	match rate (%)
trans-mitral diastolic inflow	start	43.71	0.81	43.70	1.00	0.9042	0.19	1.00	81.11
	Epeak	53.98	1.11	54.12	1.07	0.9009	0.21	2.00	81.11
	Apeak	95.36	3.91	95.43	3.88	0.9954	0.14	1.00	85.56
	end	99.80	3.86	99.79	3.96	0.9989	0.03	1.00	96.67
trans-aortic systolic outflow	start	4.66	0.74	4.56	0.75	0.8977	0.12	1.00	87.78
	Vpeak	14.76	0.95	14.93	0.83	0.9157	0.18	1.00	82.22
	end	36.70	0.55	36.62	0.57	0.8856	0.08	1.00	92.22

To reduce the uncertainty and inaccuracy that manual analysis is subject to, the two observers, who had performed four individual readings, subsequently met to resolve differences of opinion and provide a joint reading which was served as a reference to assess the automatic results. In the echocardiographic flow images used for the research, the maximum possible number of grayscale levels is 200. This is more than adequate for human perception since in general the human visual system can visually discriminate about 30 different gray shades between white and black in a single image [6]. Therefore during the joint reading, pseudo-color rather than the original gray-color was used to display trans-valvular flow images for better feature discrimination.

In order to give an overview of the performance of the developed system, the mean and standard deviation of seven selected timings obtained using the joint reading and the automatic system were calculated. The mean and maximum of linear absolute error values are calculated as distance between computer identified and manual drawn timing points described previously. The correlate coefficients of seven selected measurements are calculated to show the degree of the agreement between manual and automatic results. The rate of perfect match (error distance = 0) of each measurement over all samples are also calculated to support the comparison. All these measures are listed in Table 3.

Clearly, results from the automatic system correlate well with the manual reference. For each of the four measurements related to MDI, the correlation coefficient between the manual and automatic analysis was greater than 0.90 with at least 81% match rate. The mean absolute difference (averaged over all 90 MDI samples) between the two analysis was less than 0.25 pixel and the maximum error distance is ranged from 1 to 2 pixels. For each of the three measurements related to ASO, the correlation coefficient between the manual and automatic analysis was greater than 0.88 with at least 82% match rate. The mean absolute difference (averaged over all 90 ASO samples) between the two analysis was less than 0.20 pixel and the maximum error distance is 1 pixel.

4. Discussion & Conclusion

Due to the physics of the spectrum-generation process, the individual characteristics of the imaging system, the presence of turbulent noise, and the inherent fuzziness in the trans-valvular blood flow signals, there exits no precise boundary to define the start and end timing of trans-valvular flows. This ambiguity represents the significant impediment to reliable analysis of spectral Doppler echocardiography automatically.

Kovacs et al have previously proposed a parameterized diastolic filling (PDF) model which is a kinematic approximation of the filling process and accounts for the E-wave and A-wave portions of trans-mitral inflow [7]. Hall et al [8,9] latterly developed an automated method of fitting the predicted contour to the selected data set of clinical maximum velocity envelope (MVE) based on the PDF model. However, the results of the modeling process are significantly dependent on the selection of the start and end points of the MVE data set [10].

The multi-stage analysis system described automatically classifies the trans-valvular flows and determines their start and end timings by specific rules. Fuzzy logic was introduced in order to incorporate spatial and timing information in the process of valvular spike detection. Through Fuzzy logic it has been possible to develop an approximate model of the reasoning perform by an ultrasonographer. Based on those initial results presented in the paper, the overall performance of the system is aggressively effective, computationally efficient, and overcomes the problems of initialization and velocity profile modeling that were encountered in the literature. Clearly it is favorable when compared with manual procedure. This encourages the further test of the system on a large population base with the ultimate aim of introducing it into routine clinical use.

5. References

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