Automated Assessment of Noninvasive Filling Pressure Using Color Doppler M-Mode Echocardography

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Abstract

Assessment of left ventricular filling pressure usually requires invasive hemodynamic monitoring to follow the progression of disease or the response to therapy. Previous investigations have shown accurate estimation of wedge pressure using noninvasive Doppler information obtained from the ratio of the wave propagation slope from color M-mode (CMM) images and the peak early diastolic filling velocity from transmitral Doppler images. This study reports an automated algorithm that derives an estimate of wedge pressure based on the spatiotemporal velocity distribution available from digital CMM Doppler images of LV filling.

1. Introduction

Assessment of left ventricular filling pressure is a common clinical problem in patients with established heart disease and usually requires invasive hemodynamic monitoring to follow the progression of disease or the response to therapy. Several non-invasive Doppler echocardiographic indices have been proposed to estimate left ventricular (LV) filling pressures measured either directly or from pulmonary capillary wedge pressures during right heart catheterization.[1,2] A recently validated index using the ratio of early transmitral filling velocities (E) to the early diastolic LV flow propagation velocity (Vp) as measured using color M-mode Doppler echo.[3]

A recent novel application of color Doppler echocardiography has been assessment of left ventricular filling by color Doppler M-mode.[4] By placing a scanline from the mid-left atrium through the mitral valve to the mid-left ventricle, a spatiotemporal velocity map of diastolic filling can be obtained. In a color Doppler M-mode image, the x-dimension is time (t) increasing to the right and the y dimension is depth (s) from the transducer increasing down the image. In epicardial or transthoracic Doppler images as shown in Figure 1, blood flow across the mitral valve is towards the transducer, from the left atrium (LA) into the left ventricle (LV).

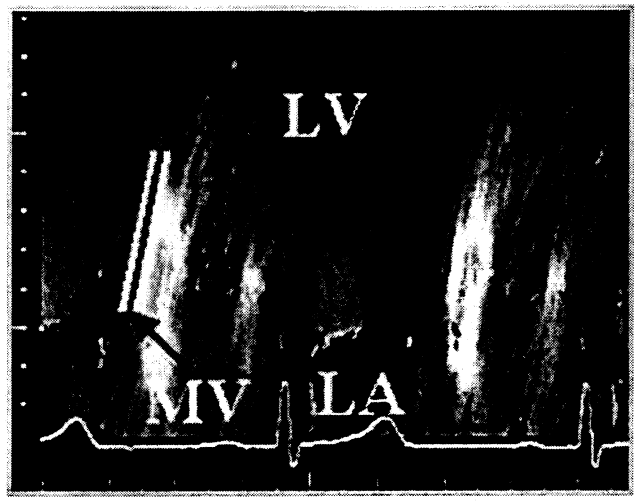

Figure 1: Color M-mode Doppler image demonstrating flow (generally color-coded) propagating from the left atrium (LA) across the mitral valve (MV) into the left ventricle (LV).

One common parameter extracted from these images is the flow propagation velocity (v_p), given by the slope of the leading edge of the color Doppler early filling (E-wave) as it passes from left atrium to left ventricle as shown in Figure 1. Note that this propagation velocity is distinct from the velocities within the propagating wave (the velocities recorded by a pulsed Doppler sample volume between the mitral leaflets), which we term the "component" velocities. Brun *et al.* found in patients with dilated cardiomyopathy, propagation velocity was only 20% of the peak E-wave (component) velocity, but these were nearly equal in normal controls.[5] They further demonstrated an inverse relationship between flow propagation velocity and ventricular relaxation time constant, ?. Stugaard *et al.* has proposed an alternative parameter of flow propagation, the temporal delay between the passage of flow at the mitral leaflet level to the ventricular apex.[6] This index, which can be obtained in a semi-automated manner from digitally output color M-mode images, was shown to be a sensitive measure of changes in ventricular filling induced by balloon angioplasty of the left anterior descending coronary artery.

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She also demonstrated delay in flow propagation in patients with dilated cardiomyopathy, changes that were examined in an *in vitro* flow model from the same laboratory. Kitabatake has proposed a third parameter of flow propagation.[7] Instead of measuring the slope of the leading edge of the color, they have chosen the slope of an aliased velocity contour near 20 cm/sec, highlighted by baseline shifting of the color display. These techniques all provide information flow propagation features that describe the filling distribution as obtained with color Doppler M-mode echocardiography.

The goal of this study, therefore, is to utilize color M-mode echocardiographic data to extract flow propagation and filling velocities to estimate filling pressures in an automated fashion. The relationship found between echocardiographically determined E/Vp and invasively determined pulmonary artery capillary wedge pressures in healthy volunteers without known cardiac disease will be examined. This approach will allow quantitative estimates of filling pressure and characterization of filling patterns objectively and reproducibly.

2. Methods

2.1. Data acquisition

Seven healthy volunteers (all male, mean age 36.6? 9.9 years) underwent standard right heart catheterization. A 6 Fr, balloon tipped, flow directed pulmonary arterial catheter (Edwards Swan-Ganz, Baxter) was placed under fluoroscopic guidance through an antecubital vein into the pulmonary artery. With the balloon inflated, the catheter was advanced into the pulmonary capillary wedge position, which was confirmed both fluoroscopically, and by the presence of characteristic pressure waveforms. All intracardiac pressures were referenced to atmospheric pressure, with the pressure transducer (Transpac IV, Abbott) zero set at 5 cm below the sternal angle in the supine position. Pressure waveforms were amplified (Hewlett Packard 78534A and Astromed ASC909) and displayed on a strip chart recorder (Astromed MT 95000) with at least 0.5 mmHg resolution. The mean pulmonary capillary wedge pressure (PCWP) was determined at end expiration. Following satisfactory measurement of baseline central venous and pulmonary capillary wedge pressures each volunteer was placed in a Plexiglas lower-body negative pressure (LBNP) box that was sealed at the level of the iliac crests. Measurements were obtained under six different hemodynamic conditions for a total of 30 measurements: Baseline, -15mmHg LBNP, -30 mmHg LBNP, repeat baseline, following rapid 15 ml/kg normal saline infusion (100 ml/min), and following an additional 15 ml/kg normal saline infusion (100 ml/min). Hemodynamic measurements and echocardiographic evaluations were performed at each stage following at least 5-10 minutes of physiologic stabilization. All volunteers tolerated the complete protocol without complications.

Echocardiographic data were obtained at baseline and during each stage of preload alteration using an ATL (Advanced Technology Laboratories, Bothell, WA) HDI 5000CV (software version 10.1) echocardiograph. The images obtained included apical 4 chamber and 2 chamber views, pulsed wave Doppler of the left ventricular inflow at the mitral leaflet tips, color M-mode of flow through the mitral valve for evaluation of transmitral flow propagation velocity. All images were stored digitally to magnetic-optical disc for later off-line image analysis.

2.2. Noninvasive assessment of PCWP

Pulmonary capillary wedge pressures (PCWP) were obtained from right heart catheterization and compared with CMM indices extracted automatically using customized LabVIEW software. The software allows for extraction of velocity information from digital CMM images using the lookup tables (color bar) provided on the images, as this information is currently not available in the DICOM format. Aliased velocities are unwrapped, if necessary, to yield the velocity distribution, V[s,t]. The software determines the early filling velocity (E) from the E-wave component as [V[s,t]]max. The flow propagation velocity, Vp, is determined by an isovelocity contour at 50% of E as shown in Figure 2. This technique of Vp determination has been recently described and has been shown to have a low intra- and interobserver variability (8% and 12%, respectively, $r>0.95$, $p<0.001$). Three consecutive measurements of Vp were averaged.

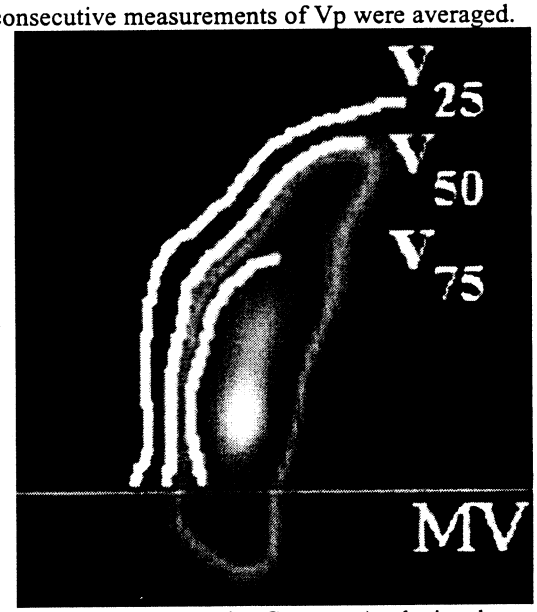

Figure 2: Isovelocity Contour Analysis where V_{50} is 50% of maximum velocity

2.3. Statistical Analysis

All statistics were performed using Systat 9.0 (SPSS Inc, Chicago, IL). One way repeated measures analysis of variance (ANOVA) was used for grouped data obtained under each stage tested. Linear regression analysis was performed to determine a relationship between each echocardiographic variable and all PCWP measurements in the entire population. Similar regression analysis was also performed to determine a relationship between variables and PCWP for each individual. Analysis of covariance was performed on variables that had a strong linear correlation with PCWP ($r>0.75$) within individuals to determine if the linear relationships observed for the entire data set could be applied to the responses of individuals. For all statistics, a p-value less than 0.05 was considered statistically significant.

3. Results

3.1. Effects of preload altering maneuvers

Under baseline conditions, PCWP ranged from 8.0 to 13.3 mmHg (average: 10.8?2.3 mmHg). The effect of lower body negative pressure is summarized in Table 1 Saline infusion resulted in a significant increase in PCWP while LBNP significantly decreased PCWP ($p<0.001$ by ANOVA). Similarly, with saline infusion E ($p<0.05$) increased, however, no significant change was observed in Vp. Conversely, with LBNP, compared to baseline, E decreased, but no significant change was observed in Vp. Of the combined indices, preload altering maneuvers resulted in significant changes in only E/Vp ($p<0.01$ by ANOVA). LBNP or saline infusion did not result in statistically significant changes in E/A.

Table 1: Effects of lower body negative pressure (LBNP) on hemodynamics and Doppler indices.

	Baseline	LBNP -15 mmHg	LBNP -30 mmHg
PCWP (mmHg)*	10.8?2.3	5.2?1.9	4.2?1.5
RAP (mmHg)*	8.6?2.0	4.4?2.0	2.5?1.2
HR (bpm)	63.2?8.2	62.4?10.8	73.0?7.75
E (cm/s)*	71.2?9.2	55.7?3.0	53.8?12.5
Vp (cm/s)	48.8?8.4	43.5?5.7	47.0?4.1
E/Vp *	1.47?0.16	1.30?0.16	1.14?0.19
E/A	1.36?0.67	1.44?0.39	1.23?0.38

3.2. Automated Assessment of PCWP

PCWP ranged from 2.2 to 23.5 mmHg. As expected in this normal population, E alone correlates well with PCWP ($y = 0.29x - 6.95$, $r = 0.92$). CMM derived E matched manual measured pulsed Doppler E ($r = 0.92$). Noninvasive E/Vp correlated well with direct PCWP ($E/Vp=0.03[PCWP]+1.05$, SEE=3.59 mmHg, $p<0.001$, $r=0.81$, Figure 3).

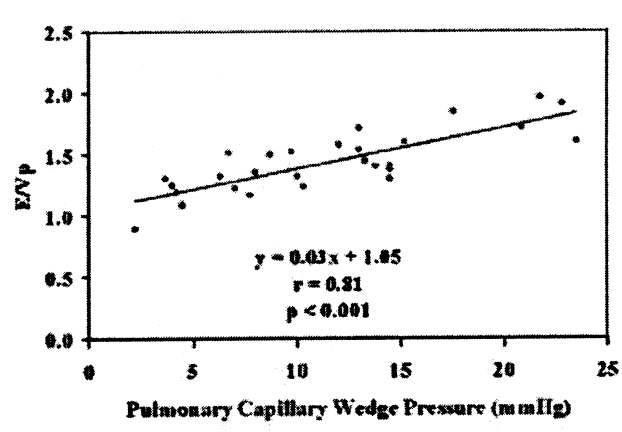

Figure 3: Relationship between automated E/Vp obtained from CMM data with direct measures of PCWP

4. Discussion

Our results indicate that in patients without underlying cardiac disease simple transmitral velocity Doppler indices can provide an accurate assessment of left ventricular filling pressures. Although this observation may be valid in patients with normal ventricular diastolic function, previous work by Choong *et al* as shown that E is strongly dependent on both preload and relaxation.[8] In their study on instrumented dogs, they showed through changes in left atrial pressures and ventricular relaxation that E was directly related to left atrial V-wave pressure ($r=0.58$, $p<0.0001$), and LV EDP ($r=0.50$, $p<0.0001$) and inversely related to tau ($r=-0.32$, $p<0.004$). To overcome the confounding effects of relaxation on using E as an index of left ventricular filling pressures investigators have proposed using combined ratios. In combing E with a relaxation *dependent*, but relatively preload *independent* Doppler index, the effects of changes in relaxation can be minimized.

Recent attention has also focused on Vp as a preload independent index of ventricular relaxation, a finding that has recently been validated in a combined human and animal study. Early work by Brun *et al* demonstrated an inverse relationship between Vp and tau. Garcia previously demonstrated that incorporating Vp into the relationship between E and PCWP could correct for the effects of alterations in ventricular relaxation.[9] He

observed that a ratio of E/Vp >1.5 predicted a PCWP > 12 mmHg (sensitivity: 79%, specificity: 89%, positive predictive value: 93%, negative predictive value: 70%). The automated assessment of CMM derived E/Vp provides a simple, non-invasive tool to accurately detect abnormal LV filling pressures.

The quantitative evaluation of Doppler velocity data has been enhanced with digital data. Local and global parameters can be extracted from the spatiotemporal velocity distribution to categorize features of interest. The post processing of the raw velocity data has also allowed noninvasive estimation of diastolic transvalvular and intraventricular pressure differences.[10,11]

5. Conclusion

Automated estimation of PCWP is achieved from CMM data using a customized analysis program that measures E/Vp and applies published equations to obtain pressure estimates. Potential integration with a clinical DICOM analysis package would permit direct estimation of noninvasive filling pressures.

Acknowledgement

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