Assessment of Transmitral Vortex Formation in Patients with Diastolic Dysfunction

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Background: Previous experimental models have related transmitral vortex formation to the longitudinal recoil of left ventricle. However, little is known about the relationships among left ventricular (LV) longitudinal relaxation, transmitral filling patterns, and LV vortex formation in clinical settings. The aim of this study was to compare the vortex formation time index among a heterogeneous group of patients with diastolic dysfunction to understand the relationship between transmitral vortex formation and abnormal diastolic filling patterns.

Methods: Echocardiographic data from 107 subjects were retrospectively evaluated. The study population was categorized into four groups on the basis of transmitral early and late diastolic Doppler filling patterns as normal ($n = 45$), impaired relaxation ($n = 14$), pseudonormal ($n = 26$), and restrictive ($n = 22$). Vortex formation time was computed from the governing equations based on transmitral flow and ejection fraction.

Results: Differences in vortex formation time index were found to be significant among all the studied groups ($P < .0001$). The trend of vortex formation during a cardiac cycle was compared in normal hearts and those with diastolic dysfunction. Mitral annular velocity (e′) was found to decrease significantly ($P < .0001$) in subjects with abnormal transmitral filling patterns compared with normal subjects. The difference in e′ among all the affected groups was not found to be significant ($P = .68$).

Conclusions: The findings of this study suggest that patients with different patterns of transmitral diastolic filling show significant changes in LV vortex formation time despite the absence of significant differences in mitral annulus recoil during diastole. (J Am Soc Echocardiogr 2012;25:220-7.)

Keywords: Vortex formation time, Transmitral filling pattern, Diastolic dysfunction, Transmitral vortex, Cardiac fluid dynamics

The topic of vortex formation inside the left ventricle (LV) has recently drawn attention because of its potential impacts on ventricular function.[1-3] It has been shown through in vitro[4-6] and in vivo[7-11] studies that a vortex rolls up along with the transmitral flow during early diastole, and finally moves toward the outflow tract. Optimal formation of the transmitral vortex ensures effective transfer of circulation, impulse, and volume and energy of the blood flow.[12] Achieving an optimal transmitral vortex requires a vigorous LV to generate adequate suction, a properly sized mitral valve that directs the blood jet through, and a normal electrical conduction system that allows ventricular events to occur in harmony. In the normal heart, the transmitral vortex assists in the effective transfer of volume, momentum, and energy[5,12] from the left atrium to the aorta via the left ventricle (LA) and minimizes the stroke work. Other biologic roles of vortex formation include rinsing the endocardial surface during diastole to avoid stasis and thrombus formation, which becomes a risk when the vortex is not well formed during diastole. It is expected that changes in LV structure and function temporarily or even permanently affect transmitral vortex formation.

Previous studies have shown that the process of transmitral vortex formation can be affected by certain clinical conditions, such as dilated cardiomyopathy, placement of artificial heart valves, and elevations of LV afterload.[10,13-15] Thus, quantification of the transmitral vortex is perhaps beneficial for the assessment of cardiac performance. The formation of vortices from pulsatile flow is typically quantified by the index of vortex formation time (VFT),[7] which is a dimensionless measure of the duration of the flow pulse (see the Appendix). The significance of VFT lies in the fact that increasing it beyond the range of 3.5 to 5.5 does not result in additional energy passing into the leading vortex. At this point, the vortex is considered optimal for efficiency and thrust.[16,17] Two independent clinical studies conducted by Gharib *et al.*[13] showed

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Abbreviations

ANOVA = Analysis of variance

EF = Ejection fraction

LA = Left atrium

LAVI = Left atrial volume index

LV = Left ventricle

LVEDV = Left ventricular end-diastolic volume

VFT = Vortex formation time

that the distribution of VFT converged to values in the anticipated optimal range of 3.5 to 5.5 in a total of 110 healthy volunteers. In the present work, we have calculated the VFT index in groups of patients with varying degrees of abnormal diastolic filling and compared the results to those in healthy subjects in order to elucidate the association between transmitral vortex formation and diastolic function.

METHODS

Study Population

Echocardiographic data from 130 subjects were retrospectively assessed from the patient database of Loma Linda University Medical Center after approval by the institutional review board. Data from 107 subjects were considered for the analyses, and all the required parameters from the available echocardiographic files were measured again for every subject to ensure accuracy. The data consisted of information from consecutive inpatients and outpatients who had been referred to the echocardiography laboratory from 2006 to 2009 for elective echocardiographic examinations. The study population was categorized into four groups of subjects as normal, impaired relaxation, pseudonormal, and restrictive, on the basis of transmitral early and late diastolic Doppler filling patterns.[18-20] Exclusion criteria were kept to minimum to allow for realistic representation of the patient population encountered at a large institution that provides primary as well as specialized health care. Patients with features that would preclude a reliable classification of filling pattern, such as severe mitral regurgitation or stenosis, prosthetic mitral valves, atrial fibrillation, and cardiac pacemakers, were excluded. Additionally, care was taken in the selection of our patient and control groups to avoid any parallel effects on the vortex formation phenomenon. The subjects in the control group did not have any signs or symptoms of cardiovascular diseases, and the patients in each group of abnormal diastolic filling were affected only by that isolated condition.

Group 1 consisted of 45 healthy subjects ranging in age from 25 to 45 years. The inclusion criteria for being considered in this group were the detection of normal cardiac rate and rhythm, normal blood pressure, no signs of acute or chronic abnormality on electrocardiography, normal Doppler criteria on the basis of Redfield *et al.*,[18] LV ejection fraction (EF) $>$ 55%, nonsmoking, and a body mass index $<$ 25 kg/m^2 according to the obesity guidelines of the National Heart, Lung, and Blood Institute.[21]

Group 2 consisted of 14 patients with impaired relaxation. The inclusion criteria for this group were the reversal of the normal E/A ratio ($<$0.75)[18] and prolonged deceleration time ($>$220 msec)[20] regardless of LA volume index (LAVI). Group 3 included 26 patients with a pseudonormal pattern of ventricular filling, represented by an E/A ratio between 0.75 and 1.5[18] and a deceleration time $>$140 msec[18] but $<$220 msec.[20] Group 4 consisted of 22 patients with a restrictive transmitral filling pattern (E/A ratio $>$ 1.5, deceleration time $<$ 140 msec)[18] and LA enlargement.

Doppler Echocardiographic Measurements

All echocardiographic examinations were performed using a Philips Sonos 5500 phased-array imaging system (Philips Medical Systems, Andover, MA). Images were available in the standard views of the LV (parasternal long-axis and short-axis and apical four-chamber and two-chamber views) taken using a 3.5-MHz transducer in harmonic mode. The routine echocardiographic data for each patient were studied. The LV EF was calculated using two methods (the Teichholz formula[22] and the biplane Simpson method[23]) and averaged over three consecutive cycles. The Doppler sample volume was placed at the tips of the mitral leaflets to obtain the LV inflow waveforms from the apical four-chamber view. All sample volumes were positioned with ultrasonic beam alignment to flow.

Transmitral pulsed-wave Doppler velocities were recorded at rest from an apical four-chamber view with a Doppler sample of 2 mm placed between the tips of the mitral leaflets. We measured peak velocities (E wave and A wave), durations, velocity-time integrals (VTIs) for early and late diastolic flow, and peak velocities in the early diastolic (e′) and atrial (a′) phases of mitral annular motion. LV end-diastolic volume (LVEDV) was estimated using the area-length method[24] on the basis of the long-axis view and a modified Simpson's rule algorithm.[25]

Planimetry was performed by direct tracing of the mitral orifice, including opened commissures, in a parasternal short-axis view. Care was taken to ensure that the cross-sectional area was measured at the leaflet tips and the measurement plane was perpendicular to the mitral orifice.[26,27] To obtain the geometric orifice area through planimetry, the optimal timing of the cardiac cycle was mid diastole. However, this was checked using the cine loop mode on a frozen image for capturing the maximal orifice area (Figure 1).[28] Although the mitral valve area changes during diastole, it takes 50 to 75 msec for the valve to fully open, which is negligible compared with the duration of the rapid filling phase (about 400 msec) when the valve is fully open. As a result, considering the maximal open area of the mitral valve may be a reasonable estimate for the diamter of the jet during the E wave.

LA volume was measured from the standard apical two-chamber and four-chamber views at end-systole. To do so, the LA borders were traced using planimetry. The LA appendage was excluded from measurement. To calculate LA volume, the biplane method of disks was used according to the chamber quantification guideline provided by American Society of Echocardiography.[23] LAVI was calculated by dividing LA volume by body surface area.[23]

Tissue Doppler imaging was performed by placing the sample volume at the lateral corner of the mitral annulus from the apical four-chamber view. The wall filter settings were adjusted to exclude high-frequency signals, and gain was minimized. Three consecutive cardiac cycles from an M-mode echocardiogram were digitized. The characteristic value for each parameter was obtained as the average of three measured parameters for each cardiac cycle.

Transmitral VFT

VFT was originally computed from the governing equations for transmitral flow and EF as[13]

$$\mathrm{VFT} = \frac{4(1-\beta)}{\pi}\alpha^3 \times \mathrm{EF} \qquad (1)$$

where β is the fraction of stroke volume contributed from the atrial component of LV filling, obtainable as