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Original Article

Advanced Age Attenuates Left Ventricular Filling Efficiency Quantified Using Vortex Formation Time: A Study of Octogenarians With Normal Left Ventricular Systolic Function Undergoing Coronary Artery Surgery

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Objective: Blood flow across the mitral valve during early left ventricular (LV) filling produces a 3-dimensional rotational fluid body, known as a vortex ring, that enhances LV filling efficiency. Diastolic dysfunction is common in elderly patients, but the influence of advanced age on vortex formation is unknown. The authors tested the hypothesis that advanced age is associated with a reduction in LV filling efficiency quantified using vortex formation time (VFT) in octogenarians undergoing coronary artery bypass graft (CABG) surgery.
Design: Observational study.
Setting: Veterans Affairs medical center.
Participants: After institutional review board approval, octogenarians (n = 7; 82 ± 2 year [mean ± standard deviation]; ejection fraction 56% ± 7%) without valve disease or atrial arrhythmias undergoing CABG were compared with a younger cohort (n = 7; 55 ± 6 year; ejection fraction 57% ± 7%) who were undergoing coronary revascularization.
Interventions: None.
Measurements and Main Results: All patients were monitored using radial and pulmonary arterial catheters and transesophageal echocardiography. Peak early LV filling (E) and atrial systole (A) blood flow velocities and their corresponding velocity-time integrals were obtained using pulse-wave Doppler echocardiography to determine E/A, atrial filling fraction (β), and E wave deceleration time. Pulse-wave Doppler also was used to measure pulmonary venous blood flow during systole and diastole. Mitral valve diameter (D) was calculated as the average of major and minor axis lengths obtained in the midesophageal LV bicommissural and long-axis transesophageal echocardiography imaging planes, respectively. VFT was calculated as $4 \times (1 - \beta) \times SV/(\pi D^3)$, where SV is the stroke volume measured using thermodilution. Systemic and pulmonary hemodynamics, LV diastolic function, and VFT were determined during steady-state conditions 30 minutes before cardiopulmonary bypass. A delayed relaxation pattern of LV filling (E/A 0.81 ± 0.16 *v* 1.29 ± 0.19, p = 0.00015; β 0.44 ± 0.05 *v* 0.35 ± 0.03, p = 0.0008; E wave deceleration time 294 ± 58 *v* 166 ± 28 ms, p < 0.0001; ratio of peak pulmonary venous systolic and diastolic blood flow velocity 1.42 ± 0.23 *v* 1.14 ± 0.20, p = 0.0255) was observed in octogenarians compared with younger patients. Mitral valve diameter was similar between groups (2.7 ± 0.2 and 2.6 ± 0.2 cm, respectively, in octogenarians *v* younger patients, p = 0.299). VFT was reduced in octogenarians compared with younger patients (3.0 ± 0.9 *v* 4.5 ± 1.2; p = 0.0171). An inverse correlation between age and VFT was shown using linear regression analysis (VFT = –0.0627 × age + 8.24; r^2 = 0.408; p = 0.0139).
Conclusion: The results indicate that LV filling efficiency quantified using VFT is reduced in octogenarians compared with younger patients undergoing coronary artery bypass grafting.
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Key Words: transmitral blood flow efficiency; vortex formation time; early left ventricular filling; fluid mechanics; diastolic function; intraventricular blood flow; advanced age; coronary artery disease

FLUID MECHANICS play an essential role in left ventricular (LV) filling dynamics. A 3-dimensional rotational body of fluid, known as a vortex ring, is generated whenever a fluid traverses an orifice,[1–3] such as when blood moves through the mitral valve.[4–7] The propagation of this transmitral ring contributes to[8] and improves the efficiency of early LV filling[9–12] by preserving fluid momentum and kinetic energy.[13] The ring inhibits stagnation of blood flow in the LV apex,[14–17] thereby reducing the risk of thrombus formation, and preferentially directs blood flow beneath the anterior mitral leaflet,[6,18] which enhances the transfer of stroke volume (SV) from the left ventricle to the proximal aorta during the subsequent ejection.[19] Transmitral vortex rings have been observed in vivo under normal and pathologic conditions (eg, cardiomyopathy, uremia, myocardial infarction) using contrast echocardiography,[17] Doppler vector flow mapping,[5,20,21] magnetic resonance imaging,[6] and particle imaging velocimetry.[13,22–24] The following 4 primary determinants of the duration, size, flow intensity, and position of the transmitral ring have been identified: (1) the left atrial-LV pressure gradient, (2) the minimum LV diastolic pressure, (3) the magnitude of diastolic mitral annular excursion, and (4) the rate and extent of LV relaxation.[2,11,25–29] Vortex ring development most often is quantified with a dimensionless parameter (vortex formation time [VFT]) derived using echocardiography.[7,30,31] VFT ranges between 3.3 and 5.5 in healthy subjects but decreases to less than 2.0 in patients with dilated cardiomyopathy.[7] A reduction in VFT is an independent predictor of morbidity and mortality in heart failure.[30] Elevated LV afterload,[32] Alzheimer's disease,[33] cardiopulmonary bypass,[34] and abnormal diastolic function[19,35,36] shorten the duration of vortex formation.

LV diastolic dysfunction is very common in the elderly.[37–40] Previous longitudinal studies showed that delays in LV isovolumic relaxation occur with age and reduce early LV filling and increase the relative contribution of atrial systole to final LV end-diastolic volume. These age-related abnormalities result from progressive LV diastolic stiffening[41] concomitant with declines in intraventricular diastolic kinetic energy[42] and diastolic suction.[43] Thus, it is likely that advanced age adversely affects LV filling efficiency, but this contention has not been examined formally. Accordingly, the authors tested the hypothesis that advanced age is associated with a reduction in LV filling efficiency quantified using VTF in octogenarians undergoing coronary artery bypass graft (CABG) surgery.

Methods

Patient Selection

The institutional review board of the authors' institution approved the protocol. Written, informed consent was waived because invasive cardiac monitoring and transesophageal echocardiography (TEE) are used routinely in patients undergoing cardiac surgery. Patients with normal preoperative LV systolic function (ejection fraction $>50\%$) undergoing CABG who were <62 or ≥ 80 years old were included in 2 separate groups. Patients with known contraindications for TEE, those undergoing repeat median sternotomy or emergency surgery, and those with valve or thoracic aortic disease were excluded. Patients with atrial fibrillation, atrial flutter, or other supraventricular tachyarrhythmias also were excluded.

Anesthetic Interventions

Each patient received intravenous midazolam (1-3 mg) and fentanyl (1-2 μg/kg) for conscious sedation. Intravenous and radial artery catheters were inserted using local anesthesia (1% lidocaine). Supplemental oxygen (2-4 L/min per nasal cannula) was provided. A pulmonary artery catheter was inserted using local anesthesia (1% lidocaine) under sterile conditions through the right or left internal jugular vein with ultrasound guidance. Anesthesia was induced using intravenous fentanyl (5-10 μg/kg), propofol (1 mg/kg), and rocuronium (1 mg/kg) and was maintained using inhaled isoflurane (end-tidal concentration of 0.5%-1.0%) in an air-oxygen mixture, fentanyl (2-3 μg/kg/h), and rocuronium (0.05 mg/kg) titrated to effect using neuromuscular monitoring. The stomach was suctioned using an oral-gastric tube, and an omniplane TEE probe (Model X7-2t, Philips, Best, The Netherlands) was advanced into the esophagus using the standard technique.

Diastolic Function and VFT

The methods used to measure LV diastolic function and calculate VFT were described in detail previously.[34–36] Briefly, pulse-wave Doppler sample volumes were placed at the tips of the mitral leaflets and within the left or right superior pulmonary vein to measure transmitral and pulmonary venous blood flow velocities, respectively. The peak LV early filling and atrial systole blood flow velocities (E and A, respectively) and corresponding velocity-time integrals (VTI-E and VTI-A, respectively) were used to calculate E/A and atrial filling fraction [β; VTI-A/(VTI-E + VTI-A)], respectively. The ratio of peak pulmonary venous systolic and diastolic blood flow velocity also was measured. The lengths of the mitral valve major and minor axes were measured using midesophageal LV bicommissural and long-axis TEE imaging planes, respectively. The maximum opening of the mitral leaflets during early LV filling was determined using visual inspection of slow motion images immediately after the T wave of the electrocardiogram. The average of the minor and major axis lengths was used to calculate mitral valve diameter (D). Cardiac output was measured using thermodilution. All