EDITORIAL COMMENT

Expanding the Frontiers of Doppler Echocardiography for the Noninvasive Assessment of Diastolic Hemodynamics*

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Clinical and experimental evidences of limitations of the simplified Bernoulli equation for assessing pressure difference across nonobstructive valves. Role of inertial forces. Doppler echocardiography has been validated extensively for the assessment of the magnitude and time course of the pressure difference across a stenotic valve using the so-called "simplified" Bernoulli equation: pressure difference (in mm Hg) = 4 × velocity (in m/s) squared that allows only for convective flow acceleration. An accurate estimate of the pressure drop by the simplified Bernoulli equation is possible because the contribution of the convective acceleration component to the transvalvular pressure difference is much greater than normal in patients with valve stenosis. However, in the absence of valve obstruction, the local acceleration effect (inertial forces) cannot be neglected, and considering only the convective forces, one introduces a substantial error in the evaluation of both magnitude and time course of pressure drop across nonobstructive valves.

Accordingly, it was not surprising to see, in the scientific literature, clinical and experimental observations reporting Doppler underestimation of transmural pressure difference across a nonobstructive valve, based solely on the simplified Bernoulli equation (3,4). In their clinical study, David et al. (3) showed that Doppler echocardiography using the simplified Bernoulli equation underestimated the actual catheterization pressure difference across a normal valve by an average of 71%. In an experimental study, Nishimura et al. (4) also showed that the transmural pressure difference calculated by Doppler using the simplified Bernoulli equation underestimated the actual catheter pressure difference by 50% in case of a normal valve.

Doppler echocardiographic estimate of the transmural pressure drop across nonobstructive valves based on fluid mechanics theory. Attempts have been made in the past to estimate in humans noninvasively, with the use of Doppler echocardiography, the inertial forces imparted to blood during left ventricular ejection and to calculate the time course and magnitude of the pressure difference across the normal aortic valve (5–8). Doppler echocardiography–derived calculations obtained by applying the generalized linear momentum equation in its integral form to the left ventricular/aortic coupling showed, in agreement with previous clinical invasive data, that the peak pressure difference across the normal aortic valve occurs well before the peak flow velocity, at the time of peak flow acceleration, and is mostly accounted for by local acceleration effect (7,8). A noninvasive method for calculating with Doppler echocardiography the early diastolic left atrioventricular pressure difference across a normal mitral valve, based on an equation of fluid mechanics describing the transmitral pressure–flow relationship, has also been reported previously (9). In this latter work (9), a clinical example showed that the peak pressure difference across a normal mitral valve occurs at the time of peak local acceleration and that it has considerably decreased at the time of peak velocity when only convective acceleration is operative. A computer simulation model, incorporating the convective and inertial terms, demonstrated that the simplified Bernoulli equation, due to the neglected local acceleration effect, may underestimate the transmural peak pressure difference up to 85% in the absence of mitral valve obstruction (9).

However, in these early published works (5–9), there was no catheter validation of the proposed methods for the noninvasive calculation of pressure drop across a nonobstructive valve. The study by Vandervoort et al. (10), published in this issue of the Journal, is unique and original because it validates, for the first time in humans, a Doppler echocardiographic method for estimating pressure drop across a normal mitral valve. The article by Vandervoort et al. (10) provides, therefore, additional evidence that Doppler echocardiography can represent a powerful tool for the assessment of the subtleties of diastolic hemodynamics.

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What do inertial forces mean physically and how should they be evaluated? Local and global inertial forces. The theoretical model used by Vandervoort et al. (10) is based on the application of differential equations of fluid mechanics that deal with infinitesimal systems and control volumes. The solution of differential equations of fluid motion provides an excellent means of determining the detailed point-to-point behavior of the flow field. Integration of the Euler’s differential equation along a streamline between two points leads to the unsteady Bernoulli equation as recalled by Vandervoort et al. (10). The obtained unsteady Bernoulli equation displays the relation of the pressure difference to the convective and local accelerations between two points of the flow field along a streamline. The proposed method that allows us to noninvasively estimate intraventricular local diastolic pressure gradients, along with other available physiologic information, may have clinical applications. In their experimental work, Courtois et al. (2,11) have suggested the importance of intraventricular regional diastolic pressure gradients. In particular, Courtois et al. (11) showed that extensive acute anterior myocardial ischemia results in attenuation, loss or even reversal of the maximum early diastolic intraventricular pressure gradient. Therefore, it would be of importance to test the sensitivity of the intraventricular pressure gradients determined by the method of Vandervoort et al. (10) as novel noninvasive markers of acute myocardial ischemia. In particular, it would be interesting to study the relation of these noninvasively calculated intraventricular local diastolic pressure gradients to the extent and location of myocardial ischemia. The approach as proposed by Vandervoort et al. (10), although validated by invasive measurements with respect to the purpose for which it was designed, allows us to study only part of the conceptual problem of the total inertial forces involved in blood motion within the heart. Conceptually, to have an estimate of the inertial forces imparted to blood in motion, one must consider not only the force acting on an infinitesimal mass of blood flowing between two points along a streamline (local inertial force) but the force required to accelerate the total mass of blood within the heart cavities (global inertial force) as well (6–9,12,13). The underestimation of the total inertial term may become important when considering the theoretical model used by Vandervoort et al. (10), especially in case of an enlarged heart with dilated atrium and ventricle. As they may constitute a significant component of the load imposed to the heart (8), the global (not merely the local) inertial forces should be measured. Using the linear momentum equation in integral form for the application of control volumes incorporating the whole atrium and left ventricle appears to provide a more appropriate description of the global inertial forces (9,13,14).

It has been suggested that transmitral flow velocity measured by Doppler echocardiography underestimates relative left ventricular inflow velocity with respect to the atrium by about 20% because of the backward motion of the cardiac base (15). This concept should be taken into account when one attempts to infer transmitial pressure differences from Doppler measurements because, from a theoretical standpoint, this is the relative velocity, and not the Doppler measured flow velocity, which is related to the transmitial pressure difference. Considering that measurements performed in the study by Vandervoort et al. (10) deal with local pressure gradients between two points along a streamline, the authors suggest that their proposed technique might be independent of intrinsic cardiac motion during early filling, such as the backward motion of the mitral annulus. However, this would imply that the intrinsic cardiac motion is homogeneous along the longitudinal axis, which remains to be demonstrated.

Finally, one of the limitations of the method proposed by Vandervoort et al. (10) is related to the Doppler technique, per se, because only differences of pressures and not absolute values at one point can be inferred from Doppler velocities. Noninvasive reconstruction of left atrial and ventricular complete pressure curves would be helpful for a better expression of diastolic function. Feasibility of generating pulmonary and right ventricular complete pressure curves from noninvasive Doppler echocardiographic signals has been reported using superimposition of Doppler-measured tricuspid and pulmonary valve flow velocities in patients with tricuspid and pulmonary valve regurgitation (16,17). In the presence of mitral regurgitation, a totally noninvasive reconstruction of the left atrial pressure curve during ventricular systole has also been reported (18). However, at the present time, no method has been described for determining noninvasively and accurately the time course of left atrial pressure during the entire diastolic period. Such an advance would allow a derivation, subsequently, of absolute values of local ventricular diastolic pressures, expanding even further the frontiers of Doppler echocardiography for the assessment of diastolic hemodynamics.

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