Space and Time Dependency of Inertial and Convective Contribution to the Transmitral Pressure Drop During Ventricular Filling

We have read with much interest the recent article by Firstenberg et al. (1), which provides new insights into the comprehension of noninvasive assessment of transmitral pressure drop. In their Figure 2, the investigators display a graph demonstrating how the inclusion of inertial term in the pressure calculation allows an estimation of pressure drop across the mitral valve closely related to the invasive measurements. In contrast, the application of the steady formulation of the Bernoulli equation implies a relevant underestimation of the pressure value with a relevant phase lag of the pressure curve. However, the relative role of convective and inertial terms for pressure generation is strongly dependent on the space and temporal distribution of the two terms, thus the Doppler-derived curve of pressure represented in their Figure 2 represents only a particular case and should not be taken as a reference for normal condition.

We have previously evaluated the pressure maps derived from the solution of Euler equations applied on numerical transformed color Doppler M-mode images of the left ventricular inflow (2,3). Because the inertial and convective terms have different space-time distribution and derive from different phenomenon (acceleration and potential of velocity, respectively), care must be taken when interpreting the transmitral pressure difference between two

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**Figure 1.** Computed pressure difference during left ventricular filling in normal conditions. Measurement points are (upper) 2 cm in the atrium, above the mitral plane, and 3 cm in the ventricle; (middle) 1 cm in the atrium and 2 cm in the ventricle; (lower) 1 cm in the atrium and 1 cm in the ventricle. Total pressure difference is reported with a thick, continuous line; the inertial (dashed line) and convective (dash-dot line) contributions are also reported separately. The thin, continuous line is the reference velocity at the mitral plane.
points. In fact, inertial drop is unaffected by the distance between measurement points when these are sufficiently outside the mitral jet core. In contrast, the convective force plays a role only when the second point is within the jet core; otherwise, its contribution is negligible.

The graph of pressure drop reported in Figure 2 of Firstenberg et al. (1) study and computed between points 5 cm apart can be misleading and of difficult interpretation because it is not linked to a space-time map of pressure. A relevant positive contribution of convection is shown there, which is always between 0.5 and 1 mm Hg during the entire filling period. This means that the velocity in the ventricle, at a distance of 3 cm from the mitral plane, must be always >25 cm/s, even in the diastatic period, which for a normal heart rate and normal flow propagation velocity is not a common finding. In addition, it is also difficult to understand how the total pressure may remain positive during the deceleration phase of the E-wave. In fact, because the inertial contribution is the flow acceleration, during deceleration the pressure increases along the direction of flow; thus, a negative atrium-ventricular pressure difference can be predictable.

From the space-temporal maps, we calculated the pressure difference among three pairs of points at different distances, and the respective results are plotted in Figure 1. As we can see, the convective term disappears when the points are separated by 5 cm (2 cm inside the atrium to 3 cm in the ventricle), a distance similar to the example by Firstenberg et al. (1). In our example, the two points are outside the jet core, and the pressure drop is zero at the maximum of mitral velocity. Figure 1 shows little changes when the two points are closer (1 cm in the atrium and 2 cm in the ventricle). In contrast, an important convective effect appears only when the second point is placed inside the jet (1 cm into the ventricle). In this case, the pressure presents a comparable influence of both terms. However, even in this case, pressure at the E-wave still presents an inversion of sign at the end of the deceleration phase when inertia is negative and velocity (convection) goes to zero.

In conclusion, we underline how convective and inertial terms of pressure are dependent from the relative position of measurement points. Space allocation of convective and inertial forces by the analysis of the atrioventricular velocity field allows a better interpretation of pressure map in hemodynamic terms.

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REPLY

We appreciate the comments of Tonti et al. regarding our recent publication (1). We agree that transmitral flow is a very complex three-dimensional process that can be approached only as an approximation when the Euler equation is applied to color M-mode images. Nevertheless, previous studies (2) using contrast agents have demonstrated that most of the streamlines of flow follow a unidirectional vector along the long axial dimension of the left ventricle (LV). The validity of this concept is further supported by the accuracy of our results. In fact, we demonstrated that this approach could quite accurately predict the total pressure drop across the normal mitral valve, an impossible task with the simplified Bernoulli equation. Tonti et al. correctly point out that display of pressure differences at just two locations misses the subtlety of the spatiotemporal pressure distribution within the LV inflow tract; our methodology, in fact, provides the full spatiotemporal map from which we extracted pressures at locations corresponding to our multisensor catheter. Tonti et al. state that the convective term should completely cancel out at a 5-cm sensor separation, but this assumes complete pressure recovery across the valve, which may not occur owing to turbulence in the inflow jet and vortices that form at the mitral tips. Indeed, if there were complete pressure recovery, there would be no net pressure drop across even stenotic valves.

The noninvasive calculation of true pressure drop across the normal mitral valve is only one application of quantitative analysis of the color M-mode Doppler image. Even more remarkably, this approach has been shown to be able to quantify the very small (1–4 mm Hg) pressure gradients between the base and apex of the LV that are a manifestation of diastolic suction. This has been validated in a canine model (3), and it was recently used to detect the 1–2-mm Hg increase in diastolic suction that occurs in submaximal exercise (4). Such gradients have been shown to decrease in ischemia (5) and increase with revascularization (6). Thus, digital image processing of color M-mode data may yield new noninvasive quantification of diastolic function that should be widely applicable in the clinical setting.

Although the measurement of the very small pressure gradients is difficult even by (perhaps especially by!) micromanometer catheters, we believe that our data are as accurate as can currently be obtained in patients, and we stand by our analysis as presented. We hope that studies such as ours (1,3,4,6) and by Tonti et al. (7) will stimulate further interest in quantitative color Doppler analysis.

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