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Magnetic Resonance Measurement of Turbulent Kinetic Energy for the Estimation of Irreversible Pressure Loss in Aortic Stenosis

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OBJECTIVES The authors sought to measure the turbulent kinetic energy (TKE) in the ascending aorta of patients with aortic stenosis and to assess its relationship to irreversible pressure loss.

BACKGROUND Irreversible pressure loss caused by energy dissipation in post-stenotic flow is an important determinant of the hemodynamic significance of aortic stenosis. The simplified Bernoulli equation used to estimate pressure gradients often misclassifies the ventricular overload caused by aortic stenosis. The current gold standard for estimation of irreversible pressure loss is catheterization, but this method is rarely used due to its invasiveness. Post-stenotic pressure loss is largely caused by dissipation of turbulent kinetic energy into heat. Recent developments in magnetic resonance flow imaging permit noninvasive estimation of TKE.

METHODS The study was approved by the local ethics review board and all subjects gave written informed consent. Three-dimensional cine magnetic resonance flow imaging was used to measure TKE in 18 subjects (4 normal volunteers, 14 patients with aortic stenosis with and without dilation). For each subject, the peak total TKE in the ascending aorta was compared with a pressure loss index. The pressure loss index was based on a previously validated theory relating pressure loss to measures obtainable by echocardiography.

RESULTS The total TKE did not appear to be related to global flow patterns visualized based on magnetic resonance–measured velocity fields. The TKE was significantly higher in patients with aortic stenosis than in normal volunteers ($p < 0.001$). The peak total TKE in the ascending aorta was strongly correlated to index pressure loss ($R^2 = 0.91$).

CONCLUSIONS Peak total TKE in the ascending aorta correlated strongly with irreversible pressure loss estimated by a well-established method. Direct measurement of TKE by magnetic resonance flow imaging may, with further validation, be used to estimate irreversible pressure loss in aortic stenosis. (J Am Coll Cardiol Img 2013;6:64–71) © 2013 by the American College of Cardiology Foundation

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Noninvasive determination of irreversible pressure loss has long been a goal of cardiovascular imaging. Irreversible pressure loss caused by energy dissipation in post-stenotic flow is an important marker of the hemodynamic significance of aortic stenosis. The left ventricle has to respond with increased work to overcome this loss of mechanical energy, resulting in increased stress on the myocardium.

The true irreversible pressure loss (net transvalvular pressure gradient, TPG_{net}) is currently best estimated by simultaneous catheter-based pressure recordings in the left ventricle and the distal ascending aorta. However, this procedure is invasive and therefore not used routinely. The current method of choice in the clinical assessment of transvalvular pressure differences is noninvasive echocardiography. Based on an estimation of the peak velocity in the vena contracta (v_{VC}) of the post-stenotic flow jet, the maximum drop in (static) pressure across the valve (maximum transvalvular pressure gradient, TPG_{max}) is estimated by the simplified Bernoulli equation in combination with the assumption that v_{VC} is much greater than the flow velocity in the left ventricle (1):

$$TPG_{max} = 4v_{VC}^2\,[\text{mm Hg}] \qquad [1]$$

The degree to which TPG_{max} represents TPG_{net} depends on the amount of kinetic energy that is dissipated distal to the vena contracta, where the flow transitions from a laminar to a turbulent state during systole. A portion of the kinetic energy that is not dissipated is converted into static pressure, resulting in so-called pressure recovery (2–9). Due to pressure recovery, TPG_{max} overestimates TPG_{net} and the increased workload imposed on the left ventricle by pressure loss (2–6). For example, a recent study reported that more than 20% of TPG_{max} was recovered in 16.8% of a large patient population (6). The clinical implications of the inability of echocardiography to account for pressure recovery are frequently debated (7–9).

A noninvasive approach to the estimation of true irreversible pressure loss could refine the diagnosis of aortic stenosis. Consequently, several investigators have proposed indexes aimed at addressing the discrepancy between TPG_{max} and TPG_{net} based on data that can be obtained by noninvasive imaging (8,10–13). These indexes typically take into account the severity of the sudden expansion that occurs between the valve and the ascending aorta, which is known to promote transition to nonlaminar flow. Despite being implicit and based on assumptions about standardized transvalvular flow patterns, such approaches have been shown to permit noninvasive estimation of irreversible pressure loss in in vitro experiments, animal models, and specific patient groups (4,11,13,14). For example, Garcia et al. (12,13) (see also Akins et al. [8]) added an energy loss term to the Bernoulli equation to account for its inability to describe pressure losses and combined that with the momentum equation. They noted that irreversible pressure loss depends on the flow rate (Q) and that it increases with decreasing vena contracta area (A_{VC}) and with increasing aortic area (A_{Ao}). When combining their results for TPG_{net} with the widely used approximation that v_{VC} is much greater than the flow velocity in the left ventricle in patients with aortic stenosis (Equation 1), the following relationship is obtained (12,13):

$$\frac{TPG_{net}}{TPG_{max}} = \left(1 - \frac{A_{VC}}{A_{Ao}}\right)^2 \qquad [2]$$

By also taking the flow rate dependency into account (12), this can be written as a pressure loss index (iPL) that can be used in patients with varying flow rates:

$$iPL = Q\frac{TPG_{net}}{TPG_{max}} = Q\left(1 - \frac{A_{VC}}{A_{Ao}}\right)^2 \qquad [3]$$

Direct measurement of the flow effects responsible for irreversible pressure loss is now possible with magnetic resonance (MR) imaging. This potentially offers a more appealing way than iPLs to correct for gross discrepancies between echocardiography and catheter-based pressure gradients. In the transitionally turbulent flow regime distal to the vena contracta, the kinetic energy can be decomposed into 2 parts: the mean kinetic energy and the turbulent kinetic energy (TKE). The dominant cause of irreversible pressure loss in clinically relevant aortic stenosis is viscous dissipation of TKE into heat (15).

Recent developments in phase-contrast magnetic resonance imaging (PC-MRI) permit noninvasive estimation of TKE (16,17). There is an important conceptual difference between PC-MRI velocity and TKE mapping. Whereas conventional PC-MRI velocity mapping estimates mean velocities based on the phase-difference between 2 complex-valued MR signals acquired with different motion sensitivity, TKE estimation is achieved by exploit-

ABBREVIATIONS AND ACRONYMS

4D = 4-dimensional (3 spatial dimensions + time)

iPL = pressure loss index

MR = magnetic resonance

PC-MRI = phase-contrast magnetic resonance imaging

TKE = turbulent kinetic energy

TPG = transvalvular pressure gradient

VENC = velocity encoding