

EDITORIAL COMMENT

Imaging Hemodynamics

The Next Frontier for CMR*

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Echocardiography is the work horse of clinical cardiac imaging, not only because it is relatively cheap to operate, mobile, and versatile, but also because it combines insight into structure and function as well as into hemodynamics through the use of Doppler. This feature of echocardiography was subsequently translated into velocity measurements of the walls of the heart and has contributed significantly to our understanding of the mechanics and function of the heart. One major limitation of tissue Doppler was the necessity for alignment of the interrogating beam with the heart wall under study. With faster computing power, speckle tracking became feasible, which overcame this alignment problem and held the promise for 3-dimensional (3D) tracking of heart motion and deformation. The robustness of 3D deformation imaging still requires improvement, and there is a lack of standardization of the different vendors' feature tracking techniques, which operate more as black boxes. Notwithstanding these limitations, 3D echocardiography as a whole has gained much use for the evaluation of valvular and congenital abnormalities (1).

Cardiac magnetic resonance (CMR) is often used as an alternative to echocardiography in those patients who have suboptimal image quality, which can reach between 10% and 30%, depending on the indication and target population. CMR is also the reference technique for structure (and function) and has major applications in tissue characterization, which are now being expanded by the use of T1 and T2 mapping and extracellular volume calculation; it is lacking, however, in easy assessment of

regional/segmental function and in hemodynamic evaluation. Valvular evaluation is possible with CMR but is relatively underused because analysis of gradients over stenotic valves, arteries, or other structures is not available.

SEE PAGE 920

Velocity measurements have always been possible with CMR but were not used in routine clinical studies. The paper by Riesenkampff et al. (2) in this issue of *JACC* could change this, because the application of 4-dimensional velocity measurements toward calculation of gradients over a coarctation could also be used across valves and, thus, may become the CMR equivalent of echocardiography Doppler. Moving beyond that comparison, as the velocities can be acquired in full 3D, CMR could be better than Doppler in elucidating cardiac hemodynamics. CMR velocity measurements in the walls can yield similar information as tissue Doppler, and much of the feature tracking used in echocardiography can be applied quite easily to CMR images. Combining wall mechanics and hemodynamics with cavity measurements to assess blood-wall interaction could become a very powerful means of better understanding and, therefore, better treating cardiac and vascular abnormalities.

Yet, is the promise raised by this paper real? Riesenkampff et al. (2) demonstrate the feasibility of an accurate noninvasive assessment of the pressure drop over an aortic coarctation. The derivation of pressure fields and hemodynamic parameters from velocity measurements always requires computational models. These can be fairly simple and direct applicable laws of physics, such as the well-known Bernoulli equation in echocardiographic Doppler hemodynamics. More extensive analyses are based on finite-element methods solving the Navier-Stokes equations (or simplifications such as the Pressure-Poisson equation in La Disa et al. [3]) in a specific anatomical domain. These solutions will depend highly on the imposed boundary conditions that

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describe the hemodynamic behavior at the boundaries, typically at the inlet and outlet, but also at the walls. These conditions can be given as velocity and pressure fields or as the relations between them. There is no doubt that an accurate measurement of spatially- and temporally-resolved 4-dimensional velocity-encoded phase-contrast CMR is a major step forward to describe the flow fields. The relation between flow and pressure at the inlet and outlets are usually defined by Windkessel models, with characteristic resistances and capacitances for all of the branching vessels. Indeed, to hemodynamically completely characterize a coarctation, the main branching into the innominate, left carotid, and left subclavian artery and descending aorta have to be modeled, each with its own characteristic Windkessel (3). In an ideal scenario, a coupling to the complete circulation would be favorable. For example, the presence of a collateral network from subclavian arteries to the descending aorta (not taken into account in the paper by Riesenkampff et al. [2]) would completely change the results of these analyses. This is the case in severe native coarctation of the aorta, which was not the target patient population in the paper by Riesenkampff et al. (2).

The results from these models will also depend on the accuracy with which one can build computational meshes from anatomical imaging. For the aorta, contrast-enhanced magnetic resonance angiography has been used extensively. However, as rightfully explained by Riesenkampff et al. (2), although a reasonably accurate delineation of the boundary is possible, accurate measurements of the 3D velocity vectors at the boundaries is currently beyond the resolution of the technique. This hampers an accurate measurement of the blood-wall interaction. As a consequence, shear stress measurements rely on a number of assumptions of the behavior of blood near the wall, and are thus “modeled.” In smooth vessels with reasonable laminar flow conditions, these assumptions are probably close to reality. To date, there is little validation of these measurements in more complicated situations where nonlaminar flow is present. To reliably quantify the interaction between blood and wall, the mechanical properties of the vessel walls also have to be known. This information is still only sparsely available for pathological vessel walls. Nonetheless, stable computational frameworks have been built to study these interactions (4).

Although the derivation of pressure fields in the setting of an aortic coarctation is feasible from a CMR and a simulation perspective, the previous description of the ingredients necessary for a complete hemodynamic characterization including blood-tissue interactions clearly shows that, for other

applications like valve hemodynamics, some further progress will be needed. Four-dimensional velocity-encoded CMR covering the complete heart is a major step forward in the assessment of ventricular flow fields and can now be assessed in a reasonable time. However, compared with the aorta, the ventricles are highly deforming structures, and an accurate time-resolved anatomical model of the ventricle from CMR remains challenging. Moreover, fast-moving thin structures like valve leaflets are not easy to segment on CMR images. This makes the meshing problem much more complicated compared with the aorta. Besides accurate anatomical mesh generation, the noninvasive estimation of absolute intracardiac pressures remains challenging, which in diastole mostly requires combination of ventricular wall properties and blood flow, increasing the number of unknowns in the model-based estimations. Again, pathological myocardial mechanical properties remain a big unknown, but (contrast-enhanced) myocardial mapping techniques (T1, T2/T2*) could provide data on regional heterogeneity.

Finally, there is the question of value: improved outcome for patients at a similar or lower cost for society. Does this new capability of CMR respond to a nonanswered question from a patient perspective? Although this new attribute could be seen as a very nice addition to CMR as a “1-stop-shop,” the question remains whether that is the right approach. Rather than pushing new technical capabilities into clinical practice, perhaps we should be better defining the remaining unresolved questions and looking for specific answers in a clinical-pathway perspective, where care is provided at the most appropriate level. This does not mean that we should not pursue technical improvements and research their applications to clinical care, but we should not add such innovations into regular clinical practice unless they replace another methodology, with proven better management and outcome for patients at similar or lower cost. Besides showing good sensitivity, specificity, and accuracy for the clinical parameters under study, an imaging modality should also impact the managing of patients and improve their outcomes before being widely adopted. An imaging platform could be a possible answer to the value proposition: the clinician poses a specific question and the platform, all imagers—cardiologists, nuclear physicians, and radiologists in collaboration—decide on the most appropriate modality for that specific patient and question, and after doing the required studies, there is an integrated report answering the original question—all within a defined budget for that type of clinical question or care pathway (5).

If and when CMR velocity-derived hemodynamic information will be included in regular clinical practice will require further technical advances and “value” testing, but from a research perspective, it could become a major technique combining within 1 acquisition wall, valve, and cavity motion, deformation, flow, and hemodynamic information that

allows a very comprehensive analysis of normal and abnormal physiology.

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