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CME

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STATE-OF-THE-ART PAPER

Emerging Trends in CV Flow Visualization

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CME Objective for This Article: At the end of this activity the reader should be able to: 1) understand relevant concepts in cardiac fluid mechanics, including the emergence of rotation in flow and the variables that delineate vortical structures; 2) elaborate on the main methods developed to image and visualize multidirectional cardiovascular flow; 3) develop dedicated imaging protocols for particle imaging velocimetry; and 4) discuss the potential clinical applications and technical challenges of determining multidirectional cardiovascular flow.

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Emerging Trends in CV Flow Visualization

Blood flow patterns are closely linked to the morphology and function of the cardiovascular system. These patterns reflect the exceptional adaptability of the cardiovascular system to maintain normal blood circulation under a wide range of workloads. Accurate retrieval and display of flow-related information remains a challenge because of the processes involved in mapping the flow velocity fields within specific chambers of the heart. We review the potentials and pitfalls of current approaches for blood flow visualization, with an emphasis on acquisition, display, and analysis of multidirectional flow. This document is divided into 3 sections. First, we provide a descriptive outline of the relevant concepts in cardiac fluid mechanics, including the emergence of rotation in flow and the variables that delineate vortical structures. Second, we elaborate on the main methods developed to image and visualize multidirectional cardiovascular flow, which are mainly based on cardiac magnetic resonance, ultrasound Doppler, and contrast particle imaging velocimetry, with recommendations for developing dedicated imaging protocols. Finally, we discuss the potential clinical applications and technical challenges with suggestions for further investigations. (J Am Coll Cardiol Img 2012;5:305–16)

Flow through the heart interacts with the mobile contours of the myocardium, valve, and vessels. Blood flowing through the sequence of compartments is subject to changes in direction and luminal diameter, and as a consequence, flow is multidirectional and vortical with a tendency to curl or spin in the cardiac chambers during various phases of the cardiac cycle (1). The valves, chamber geometry, and wall motion modify the flow patterns to produce a hemodynamic environment comprising normal or pathological adaptation. Therefore, analyzing the spatial and temporal distribution of blood flow in the cardiovascular system may provide diagnostic and prognostic information. However, acquiring and visualizing flow through the volumes of the heart cavity is a complex topic. Doppler echocardiography and cardiac magnetic resonance (CMR), in different ways, have been used to measure the velocities of the flow that is predominantly unidirectional while it passes through a valve, a jet, or an approximately cylindrical vessel segment. Recent technological innovations in imaging modalities and the emergence of flow visualization techniques have provided valuable opportunities for direct in vivo assessment of multidirectional blood flow. Analysis of the flow fields is associated with variables such as pressure differences, shear stresses, and energy dissipation. The display and measurement of such flow variables on a page or 2-dimensional (2D) computer screen can be challenging, and each variable calls for different types of analysis and representation. Therefore, there is a pressing need to guide and advance flow visualization techniques toward the development of consistent measurements and clinical applications (2).

Basic Principles in Cardiovascular Fluid Mechanics

Blood is a corpuscular material that behaves like a fluid and can be deformed throughout its volume. Its movements are powered and constrained by the movements of containing boundaries. Blood's patterns of flow are subject, on the one hand, to the directional momentum of the streams entering and moving through the chambers and, on the other hand, to the slowing, frictional effect of the viscosity both relative to the boundaries as well as between streams, with different velocities sliding against one another within the volume. The liquid motion can be imagined as being composed of numerous flexible layers (laminae) sliding relative to each other (Fig. 1A).

Laminar flow, in which the directions of streamlines remain almost parallel to those of neighboring streamlines or boundaries, occurs in the smaller, more peripheral blood vessels, but it is not typical of flow through large vessels or the chambers of the heart. Laminar flow tends to become unstable, fragmenting and mixing with eddies and counter-eddies when its kinetic energy (which is proportional to the square of its velocity [V]) becomes large relative to its rate of energy dissipation (which is roughly proportional to $\nu V/D$, where D is the diameter of the vessel and ν is the kinematic viscosity). When this ratio, known as the Reynolds number ($Re = VD/\nu$), exceeds a critical value (approximately 2,500 for steady flow in a straight