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SCIENTIFIC EDITORIAL

Four-dimensional flow cardiovascular magnetic resonance: Towards accurate flow quantification?

IRM cardiovasculaire 4D des flux : vers une quantification précise des flux ?

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Cardiovascular magnetic resonance (CMR) has become an important tool for the clinical assessment of patients with cardiovascular disease. Besides morphological information, CMR provides functional information on cardiac function, perfusion, myocardial viability and blood flow. Phase contrast CMR (PC-CMR) relies on the direct relationship between blood flow velocity and the phase of the magnetic resonance signal. Two-dimensional (2D) cine PC-CMR yields a series of anatomical (magnitude) and flow velocity (phase difference) images that represent the temporal changes in morphology and blood flow over the cardiac cycle. The 2D location is positioned normal to the direction of the vessel, with typical imaging parameters: spatial resolution 1.5—2.5 mm; temporal resolution 30—40 ms; slice thickness 5—8 mm. 2D PC-CMR is a routine part of standard CMR for the assessment of regional blood flow in the heart and great vessels [1,2]. The velocity encoding sensitivity (Venc), which represents the maximum flow velocity that can be acquired, is set by the operator to avoid velocity aliasing, but also minimize velocity noise.

More recently, time-resolved PC-CMR, with velocity encoding along all three flow directions and three-dimensional (3D) anatomical coverage (four-dimensional [4D] flow CMR), has been applied for the evaluation of cardiovascular haemodynamics. Whole heart 4D flow CMR is acquired using electrocardiography and (usually) respiratory motion compensation. 3D velocity encoding is used to obtain velocity-sensitive phase images, which are subtracted from reference images to calculate blood flow velocities along all three spatial dimensions (Vx, Vy and Vz).

Abbreviations: 2D, two-dimensional; 3D, three-dimensional; 4D, four-dimensional; CMR, cardiovascular magnetic resonance; PC-CMR, phase contrast cardiovascular magnetic resonance.

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The acquisition generates a 3D anatomical representation of the underlying cardiovascular geometry needed for 3D flow visualization and retrospective flow quantification. 4D flow CMR can provide information on the temporal and spatial evolution of 3D blood flow, with full volumetric coverage of any cardiac or vascular region of interest (at least 40 ms temporal resolution). A flexible retrospective quantification may be assessed at any location within the 3D data volume on an off-line workstation, and provides variables such as total flow, flow-time curves, peak velocities, pressure gradients or regurgitant fraction [3,4]. The combination of 3D blood flow visualization with flow quantification enables unprecedented comprehensive evaluation of the impact of cardiovascular diseases on global and local changes in cardiac or vascular haemodynamics [5,6].

Recent technical developments, including the utilization of advanced parallel imaging techniques, have resulted in reasonable overall scan times of < 10 minutes for 4D flow CMR of the aorta or whole heart coverage, depending on the breathing patterns and heart rate of the patients. Continued developments in sparse sampling techniques (compressed sensing, radial acquisition and k-t GRAPPA) or multidimensional parallel imaging might further improve scan times. The clinical application of 4D flow CMR has become more feasible, as illustrated by the large number of recent reports on the clinical utility of the technique. Some 4D flow CMR studies have compared blood flow variables with markers determined by Doppler ultrasound and echocardiography, such as peak pressure gradient ($r = 0.96$; $P < 0.05$) [7] or peak and mean velocities ($r = 0.83$ and $r = 0.76$, respectively) [8]. In addition, 4D flow CMR can provide improved clinical haemodynamic assessment, by deriving additional metrics of cardiovascular haemodynamics, such as wall shear stress [9], pressure difference [7,10], pulse wave velocity [11] or turbulent kinetic energy [12]. Data have shown excellent agreement with 2D cine PC-CMR for flow quantification [13]. Furthermore, 4D flow CMR has good scan-rescan reproducibility and low interobserver and intraobserver variability of flow quantification for intracranial, cervical, thoracic and abdominal applications.

4D flow CMR has been applied and validated in many clinical applications. We will provide a concise and non-exhaustive overview. 4D flow CMR may be very useful for congenital heart disease, and whole heart techniques allow for a noninvasive comprehensive assessment of cardiovascular haemodynamics in the heart and surrounding great vessels, with flexible off-line quantitative analysis in any plane. 4D flow CMR is also very useful for diseases of the thoracic aorta. In patients with bicuspid aortic valve and aortic aneurysm, 4D flow CMR has shown high velocity flow jets impinging on the ascending aortic wall and resulting in increased wall shear stress, as well as increased helical flow in the ascending aorta [14]. Patients with aortic coarctation have flow jet eccentricity following the coarctation, resulting in jet impingement along the descending aorta. 4D flow CMR facilitates a comprehensive velocity assessment throughout the entire affected region near the coarctation [15]; it allows for direct accurate quantification of intracardiac shunts, and may show potential for aortic and pulmonary valve stenosis and regurgitation. 4D flow data may provide more advanced metrics of haemodynamics associated with complex blood flow patterns, such as highly helical flow in aortic valve disease. These variables include the quantification of vorticity, helicity, flow angle, wall shear stress and turbulent and viscous energy loss. Alterations in these haemodynamic variables may affect signalling and organization of endothelial cells. 4D flow may bring new insights in the assessment of hepatic and portal venous flow of patients with advanced liver cirrhosis.

Errors and limitations

There are various sources of phase offset errors in 4D flow CMR that can alter image quality and impair measurements. The most common include phase offset errors due to Eddy currents, Maxwell terms and gradient field non-linearity. Appropriate correction strategies must be applied to compensate for these potential sources of error before processing of the data. The corrections for Maxwell terms and gradient field non-linearity are performed during image reconstruction, without user interaction. Correction for Eddy currents has to be integrated into the data analysis workflow. The approach is based on thresholding, to identify regions with static tissue. These regions are then used to estimate Eddy current-induced linearly varying phase offset errors, which are subsequently subtracted from the entire image. Postprocessing is time consuming, and is performed off-line on specific workstations. Limited spatial resolution is a drawback for analysis in small vessels. An additional barrier to the widespread clinical implementation of 4D flow CMR is the lack of validation against clinical gold standards, e.g. invasive measurements of blood flow variables. A common effort is needed to work toward increased availability and clinical adoption of 4D flow CMR, by refining the clinical 4D flow workflow, determining the most useful ways to present the data and enabling quick data postprocessing in the archive systems.

Disclosure of interest

The author declares that he has no competing interest.

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