Why 4D Flow MRI? Real Advantages
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This special issue of Magnetic Resonance in Medical Sciences features the most recent reviews on 4D Flow MRI. These reviews deal with the current status of the emerging technique of 4D Flow MRI facilitated in various areas that are difficult to obtain with conventional flowmetry. MR signals inherently contain flow velocity information. In previous decades, in vivo blood flow measurement was traditionally performed by 2D methods, such as Doppler ultrasonography and 2D phase-contrast MRI, which have long been regarded as mature techniques in hemodynamic flowmetry. Although 2D velocimetries have many advantages over 4D Flow MRI in terms of cost and accessibility, and provide excellent temporal and in-plane spatial resolutions, they also have some disadvantages. The emerging technology of 4D Flow MRI can overcome the shortcomings of conventional 2D imaging. In recent years, hemodynamic analysis has witnessed significant progress that is primarily attributable to advances in 4D Flow MRI.

Keywords: cardiovascular imaging, 4D flow magnetic resonance imaging, magnetic resonance imaging, phase-contrast image

Advantages of 4D Flow MRI

Retrospective flowmetry
4D Flow MRI is a technique that provides 3D velocity vector information of the fluid in a cardiac phase-resolved manner. A unique advantage of 4D Flow MRI is “retrospective flowmetry.” Unlike other 2D modalities, 4D Flow MRI can allow measurements of the blood flow velocity of any vessels in the FOV in any measurement sections, even after the patient has left the MR suite. This feature is particularly useful when many measurement points are required in a single examination.

Reliability of flow measurements
Thus far, 2D phase-contrast MRI has been the bedrock of MR flowmetry and is regarded as the gold standard. However, the accuracy of 2D flowmetry is ensured by the assumption that the intravascular blood flow is laminar. In 2D flowmetry, it is difficult to delineate the flow patterns (i.e., vortices or helices) in the vessels. Therefore, it is challenging to optimize the measurement section blindly. In 4D Flow MRI, non-laminar flows can be depicted via streamline analysis to avoid the segment in the measurement.1 As long as the flow is laminar, the same flow volume data should be obtained regardless of where the measurement section is located in the same vessel, termed “the conservation of mass principle.” However, a specific Reynolds number is required for the flow to be laminar. Therefore, many portions of the blood flow in the vessels are non-laminar; this is one of the reasons for a mandatory 3D depiction of the streamlines before flowmetry. Such non-laminar flow segments should be avoided for proper flowmetry.

Various physiologically relevant indices of hemodynamics can be derived from velocity vectors
4D Flow MRI has many velocity-vector-derived indices that have been suggested to be linked with various cardiovascular physiologies and pathologie.2–5 These indices, including wall shear stress (WSS), oscillatory shear index, viscous energy loss, pulse wave velocity, and pressure gradients, have been developed as potential biomarkers that can be easily calculated and displayed by generating the 3D flowmetry data.6–11 Such biomarkers are clinically validated in various investigations and used in many cardiovascular studies, as discussed in this special issue.12–17
Current Limitations of 4D Flow MRI

Although 4D Flow MRI has many advantages, some shortcomings need to be addressed. The current limitations and their potential solutions are as follows:

Long imaging time

4D Flow MRI was introduced to the clinical environment in the early 2000s. Until then, the 3D cine phase-contrast method with conventional technologies was known to suffer from a protracted imaging time of nearly one hour for the whole-heart imaging, which was not clinically viable. With the advent of 4D Flow MRI, the imaging time was significantly shortened to around 10 min; however, the current clinical environment requires an even shorter imaging time. The imaging time can be further shortened to a few minutes by using recent cutting-edge technologies such as echo-planar imaging and sparse imaging.

Optimization of velocity encoding

Currently, there is only one velocity encoding (VENC) that can be applied in a single session of the scan; hence, the actual flow velocity may often exceed this value. The blood flow velocity in the same blood vessel varies among individuals depending primarily on their age. Similarly, different blood vessels within the same individual will have different flow velocities. Even within the same blood vessel, the blood flow is slow near the wall and fast in the center. Therefore, it is not reasonable to obtain measurements uniformly with a single value of the VENC setting. To solve this problem, the dual VENC method was developed, which allows two VENCs to be set. For example, the data acquired with higher VENC may be used for assessing arterial velocities, and lower for venous.

Gating to physiological motion

It is important to note that time-resolved images provided by 4D Flow MRI do not represent the flow occurring in real time, but an average value acquired from many cardiac cycles with electrocardiogram (ECG) synchronization. To depict the flow not synchronized with the heartbeat, it may be necessary to adopt other techniques; image averaging may not be suitable for representing such sporadic and unsteady flows. A spin-labeling technique or saturation band to chase the signal void on ultrafast hydrography and display it as a movie may be one solution.

Venous blood flow and cerebrospinal flow are known to be affected by respiratory movement together with the cardiac phase. Nevertheless, standard 4D Flow MRI collects data using ECG gating only, which does not reflect hemodynamic changes due to longer cycles of physiological motions such as respiratory motion. By simultaneous acquisition of the flow velocity data using ECG and respiration gating, new insights into physiological hemodynamics may be gained.

Quality Control of 4D Flow MRI

Recently, 4D Flow MRI has been implemented in commercially available MR systems as a product basis; therefore, numerous studies with a large amount of research data have been reported. However, some reports seem to be questionable in terms of whether they have conducted proper flow phantom studies and validations concerning the integrity of the flow velocity measurements of their own devices. In reality, different velocity measurement values may be obtained from MR scanners of other vendors even when similar pulse sequences are employed, and the same flow phantom is tested for measurement. It is not easy to uniformly interpret the data between models for measurement values.

In general, the accuracy of the measured velocity is strongly dependent on the SNR of the phase-contrast images. As there is often a trade-off between imaging speed and SNR, one must be cautious about simply accelerating the imaging process. Careful attention must be paid to the balance between spatial resolution and SNR in 4D flowmetry. The setting of optimal VENC is essential for maintaining an adequate SNR. Similarly, accurate determination of the vessel wall boundary is often crucial for calculating important biomarkers such as WSS. However, such calculations may not always be accurate owing to vascular pulsatility or segmentation errors due to a lack of luminal SNR. The simplest way to increase SNR may be acquiring the 4D Flow MRI immediately after the study that requires gadolinium-based contrast media administration.

Future Prospects

As MRI is a non-invasive and ionizing-radiation-free technique and does not require contrast administration in most cases, it can be used for healthy individuals, not just patients.

With rapid developments in highly accelerated imaging and cutting-edge technologies including artificial intelligence, 4D Flow MRI is expected to achieve even higher speeds at lower costs. As 4D Flow MRI can provide comprehensive spatio-temporal velocity vector data closely related to vascular pathophysiology, it can contribute toward public health in terms of predicting and preventing not only vascular diseases but also many other diseases in the near future.

Conflicts of Interest

The corresponding author Yasuo Takehara is an endowed chair of a department that is financially supported by a private company; however, this status is irrelevant to the contents of the paper.
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