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4D Flow Meets CT: Can It Compete with 4D Flow MRI?

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Conflicts of interest are listed at the end of this article.

See also the article by Lantz et al in this issue.

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The noninvasive evaluation of intracardiac hemodynamics has been a topic of interest for researchers and clinicians for nearly 2 decades (1,2). While Doppler echocardiography provides details regarding certain blood flow parameters in a noninvasive fashion, recent technologic advances in MRI have made it possible to acquire a three-dimensional (3D) volume with velocity parameters, which is encoded in three spatial directions by using four-dimensional (4D) time resolved phase-contrast imaging, also known as "4D flow MRI." Four-dimensional flow MRI is generally performed to visualize intravascular and intracardiac flow patterns by displaying streamlines, velocity vectors, or particles. However, 4D flow MRI can also be used to derive quantitative information pertaining to blood flow, particle tracing, or even kinetic energy in any retrospectively defined measurement plane. Increased use of 4D flow MRI has led to a number of promising applications in various fields of medical imaging, such as neuroradiology and cardiovascular imaging (3,4), as well as the development of a consensus guideline regarding the technique's clinical and investigational utility (5). However, recent research suggests that MRI is no longer the only player in the 4D flow arena. Despite the substantially different technologic basis, theoretical background, and computational requirements, the derivation of 4D flow data from CT acquisitions has become a reality.

In this issue of *Radiology*, Lantz and colleagues (6) report the feasibility of intracardiac 4D flow CT in a small prospective cohort and compare their quantitative measurements to those at corresponding 4D flow MRI. Three expert observers analyzed intracardiac left ventricular flow characteristics in 12 study participants, including basic flow parameters, kinetic energy, and the four major intracardiac flow components: direct flow (blood enters and exits the left ventricle in the same cardiac cycle), retained flow (blood enters but resides), delayed ejection flow (blood exits in systole), and residual flow (blood resides for at least two cardiac cycles). Overall, 4D flow CT provided very similar flow patterns and measurements compared with MRI. Notably, the authors reported significantly lower stroke volume with CT versus MRI; however, this was attributed to potential differences in the acquisition technologies and respiratory commands (ie, 4D flow MRI was acquired in a free-breathing fashion with respiratory navigation, while 4D flow CT data were collected at slight inspiration). Intracardiac flow components showed good agreement between the two modalities with less than 5% overall bias, while the strongest correlation was found in the direct and residual flow components.

The presented 4D flow CT analysis is based on computational fluid dynamics, a technology that is able to model the interaction of liquids with different surfaces. While computational fluid dynamics was initially developed for the aerospace industry to evaluate the aerodynamics of different spaceships, aircrafts, and even automobiles, the technology has seen growing utilization in the medical sciences. The most recent application of computational fluid dynamics that has achieved implementation into clinical workflows is coronary CT angiography–based fractional flow reserve (7), a potential game-changer for the evaluation of patients suspected of having coronary artery disease. While it is premature to predict similar success and traction for 4D flow CT analysis, there are potential advantages to the technique that may address certain limitations of 4D flow MRI, such as the long acquisition times and limited spatial resolution.

One of the clear advantages offered by 4D flow CT over 4D flow MRI, as highlighted by Lantz et al, is the ability to use conventional clinical coronary CT angiography data sets without the need for additional imaging (ie, 4D flow CT analysis can be retrospectively performed). In contrast, 4D flow MRI requires a dedicated acquisition, which can add an extra 5–20 minutes to the overall examination duration, depending on the MRI pulse sequence used. It is worth noting that 4D flow CT postprocessing requires full coverage of the cardiac cycle, meaning only retrospectively gated coronary CT angiography data sets are suitable for the analysis. Unfortunately, the application of retrospective gating for the sole purpose of data set compatibility for 4D flow CT analysis may result in a higher radiation dose for the patient; however, as reported by the authors, the average radiation dose can be kept at an acceptable level (5.39 mSv) using a third-generation dual-source CT system. Moreover, there are two additional advantages of the CT technique over MRI that arise from technologic differences between the two modalities. First, the flow visualization in a single cardiac cycle reconstructed from an entire 4D flow MRI data set does not represent an actual, real cardiac cycle, as the data are collected and averaged through hundreds of consecutive heartbeats. On the contrary, coronary CT angiography is able to capture the entire heart in a few heartbeats (three cardiac cycles in the current study), thus rendering a negligible variance between cardiac cycles. Second, the difference in spatial resolution between CT and MRI approaches a 10-fold level (0.35 vs 2.9 mm). The

improved spatial resolution of CT may therefore provide a more detailed evaluation, especially in terms of particle tracing.

As with every new technique, 4D flow CT faces certain limitations to its clinical implementation. While postprocessing of a 4D flow MRI data set can be time consuming and requires substantial computational power, this becomes increasingly true for 4D flow CT. As reported by Lantz et al, the computational time for analysis may reach up to 10 hours for each cardiac cycle, even when a recon box with 96 cores is used. While such a powerful computer is generally unavailable, the current Matlab-based data processing poses further challenges to a clinical imager. Improvements in computational time and the development of a user-friendly graphical interface would certainly enhance the interest in the field and increase the chances of clinical implementation.

Indeed, it is important to interpret the results from this study carefully. The limited size and substantial heterogeneity of the patient population may fulfill the purpose of a technical feasibility evaluation; however, much larger prospective patient cohorts are needed to address many remaining questions. For example, it would be important to assess how 4D flow CT evaluation can be standardized across a wide variety of CT systems. Newer generations of CT instruments, such as the one used in the current study, tend to provide better spatial and temporal resolution, with higher image quality and lower image noise. It would be interesting to see how older systems perform given their relative technical limitations. Furthermore, the impact of CT image quality, contrast material timing, or even the applied CT protocol (eg, coronary CT angiography vs "triple-rule-out" CT) on 4D flow CT performance should be evaluated. Once technical concerns have been adequately addressed, the clinical utility of 4D flow CT can be explored. This is especially true for targeted patient groups, such as patients with congenital heart disease, in which the majority of MRI flow measurements are performed.

In conclusion, the results from this proof-of-concept study debut the 4D flow CT technique as a promising alternative to 4D flow MRI with its own unique benefits and limitations. Undoubtedly, the potential to further complement coronary CT angiography is what drives the field's intrigue regarding 4D flow CT analysis. Decades ago, when coronary CT angiography became clinically feasible, it was only able to provide anatomic information about the heart, while functional assessment required alternative imaging modalities. With the introduction of CT myocardial perfusion imaging (8) and, subsequently, CT-derived fractional flow reserve (7), multiple layers of functional assessment have been effectively implemented and are paving the way for future techniques. With the potential clinical advent of 4D flow CT, a third aspect of functional analysis would become feasible, further contributing to the use of CT as a "one-stop shop" imaging modality.

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