Clinical Implementation of 4D Flow MRI in a Large Cardiovascular Imaging Practice: Motivation, Strategies, and Initial Experience

Ryan J. Avery, M.D.1; Bradley D. Allen, M.D., M.S.;1 Fei Fei Gong, M.D.2; Rachel Davids, B.S.R.T.(R)(MR)MRSO(MRSC)3; Marci Messina, RT(R)(MR)MRSO(MRSC)1; Kelvin Chow, Ph.D.3; James C. Carr, M.D.1; Michael Markl, Ph.D.1

1Department of Radiology, Northwestern University, Chicago, IL, USA
2Bluhm Cardiovascular Institute, Northwestern University, Chicago, IL, USA
3Cardiovascular MR R&D, Siemens Medical Solutions, USA Inc., Chicago, IL, USA

Like most sites during the initial onset of the COVID-19 pandemic, we sought to reduce exposure by dramatically reducing our dedicated clinical and research MRI scanning to a low quantity, resulting in both outpatient and research scanning being markedly reduced. During this period, our staff took this opportunity to set-up a working group in order to advise on scanner efficiency regarding our current cardiovascular MRI (CMR) scanning protocols. Given that our institution performs a high volume of CMR scans that utilize multiple 2-dimensional phase-contrast sequences to evaluate the flow across both the aortic and pulmonic valves and throughout the course of the aorta, our group decided that a concerted effort to fully implement four-dimensional phase-contrast imaging (hereafter referred to as 4D Flow) could improve scanner efficiency and perhaps provide more consistent flow quantification. This goal was implemented with the expectation that overall MR operations would be streamlined by both eliminating the numerous breath-hold 2D phase-contrast image acquisitions and decreasing technologist sequence planning time, while simultaneously improving patient comfort with the free-breathing 4D Flow sequence in cases requiring vascular flow evaluation.

Heterogeneity all around

Previous considerations of clinical implementation of 4D Flow proved daunting, given the difficulty of uniformly setting up a sequence notable for requiring a longer (~10 min) acquisition time, unique spatial planning, and balancing multiple parameters including velocity encoding, phase oversampling, and field of view (FOV), and the time necessary for inline reconstruction of the large volume of data involved. These factors were further complicated by an additional order of complexity, since many different MR scanners are utilized for CMR at our institution. For instance, our hospital has multiple 1.5T and 3T MR scanners, but we currently perform 4D Flow only on 1.5T

A screenshot of the scanner workstation interface during the planning of the 4D Flow sequence: The three images are from the 3-plane TrueFISP localizer. Notice that the yellow acquisition box has a coronal orientation with complete inclusion of the thoracic aorta. On the axial image (far left), it is evident that the main pulmonary artery and its right branch are included in the acquisition.
scanners, reducing the complexity of our implementation by a single level. However, a uniform implementation of this sequence on multiple different types of 1.5T scanners was still a challenge. While the 1.5T scanners that we utilize for cardiovascular imaging with 4D Flow are all manufactured by Siemens Healthineers, we were still faced with a heterogeneous installation since our institution routinely utilizes 3 different models of scanners: MAGNETOM Sola, MAGNETOM Aera, and MAGNETOM Avanto. Since the MAGNETOM Sola and MAGNETOM Aera are the most recent types of scanners, we will limit the discussion of our installation to these scanners, given that we expect most readers will be working on a similar platform. Furthermore, our work with this implementation of 4D Flow on the older MAGNETOM Avanto MR scanners utilized techniques that may not be widely able for implementation by our current audience, so further discussions of the Avanto will not be included.

Uniformity across different platforms

Our previous 4D Flow pulse sequences used an earlier version of the 4D Flow works-in-progress (WIP)\(^1\) that was prospectively ECG-gated. While this version was useful for detecting peak velocities, prospective gating is suboptimal for flow analysis, because a portion of diastole is not acquired, thus limiting certain analyses such as mitral regurgitation quantification. For this project, our MAGNETOM Sola and MAGNETOM Aera scanners were both updated to a newer version of the 4D Flow WIP\(^1\) pulse sequence, allowing us to perform a retrospective ECG-gated sequence providing complete analysis of the cardiac cycle and the flow of the associated vascular structures. Since this sequence was available for both our MAGNETOM Sola and MAGNETOM Aera scanners, it provided a unique opportunity to improve sequence acquisition uniformity. Our goal was to provide a complete phase-contrast evaluation of the cardiac cycle across our MR platforms with the expectation of a uniform dataset that would be comparable regardless of patient pathology or scanner type. Given that our previous use of 4D Flow was dictated by the clinical indication for the exam, sequence spatial coverage had previously been set up in order to interrogate specific vascular structures (e.g., a sagittal oblique volumetric slab performed with complete coverage of the aorta). However, indication-based FOV selection can too often lead to errors related to coverage planning or miscommunication in regard to the indication for the exam. In order to simplify set-up and reduce the chances of spatial acquisition errors or incomplete evaluation of vessels, our team agreed that our goal would be to perform a sequence that could be uniformly applied to all patients and was acceptable regardless of the anatomic structure being evaluated. With these constraints in mind, we agreed that acquisition of a coronal slab, which could be quickly and relatively easily planned by the technologist using the 3-plane localizer sequences (Fig. 1), would provide an ideal solution. The slab would be planned with the primary objective of covering the entire aorta while limiting the slab to exclude the sternum anteriorly and avoiding the soft tissues posterior to the descending thoracic aorta. This consistent target would simplify the planning for our technologists and provide a uniform anatomic assessment for easier post-processing and analysis (Figs. 2A, B).

\(^1\) Work in progress: the application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.
The slab

Clinically, the spatial planning of a single coronal slab of the chest satisfied our primary goal of acquiring complete thoracic aorta coverage and ensuring that each exam would enable a comprehensive evaluation of the entire thoracic aorta that could be used for all aortic pathologies commonly encountered (Fig. 3). An additional advantage of routinely implementing 4D Flow via this approach is that it gives us the opportunity for post-hoc flow evaluation of both the aorta and the aortic valve, which could provide quantitative analysis of any previously undiagnosed aortic pathology without requiring a priori planning. Additionally, the coronal slab spatial acquisition generally includes the entire main pulmonary artery and its branch vessels, pulmonary veins, and vena cavae, which could be used for verification of consistent flows throughout the left and right cardiac chambers, and their respective great vessels, and for verification of these flows relative to volumetric stroke volume analysis from cine data, to better calculate valvular insufficiency or shunt (Fig. 4). Also, given the emerging use of 4D Flow for intracardiac pathology evaluation, this coverage plan would be able to routinely investigate the atrioventricular valves and the left ventricular outflow tract (Fig. 5).

While our primary goal for spatial planning was to achieve both appropriate and uniform anatomic coverage, we elected to also simplify the approach by limiting additional parameters that should be considered during image planning. To simplify planning by our technologist, our group decided that coronal orientation would always be used with no adjustment to the orientation, such as a coronal oblique orientation. Furthermore, we established a FOV that would not be adjusted in order to maintain a 2.6 x 2.6 mm in-plane spatial resolution that would be acceptable for accurate diagnostic quantification of vascular flow. In order to avoid spatial aliasing in larger patients with wide shoulders, we implemented 20% phase-encoding oversampling to the sequence. While ECG gating is necessary to maintain temporal resolution, our group evaluated the necessity to alleviate breathing-related motion artifacts via respiratory navigation (Fig. 6). Since the coronal view is less susceptible to motion artifacts, we tested the sequence without respiratory navigation. The images without respiratory navigation suffered from no appreciable motion artifacts and did not have the area of signal loss in the right chest that occurs due to the navigator slice. Given that this approach provided a clinically acceptable sequence while further streamlining set-up by foregoing technologist planning of the navigator slice, and faster image acquisition since images could be acquired continuously (without navigator efficiency limitations), we felt this was an acceptable trade-off. However, we do acknowledge that this technique will require further data analysis to confirm accuracy.

3 Cropped view of the 4D Flow coronal slab after post-processing demonstrates pathline visualization of flow throughout the thoracic aorta.

4 Post-processed view of the 4D Flow coronal slab, including cropping and segmentation to allow visualization of flow via pathlines within the main pulmonary artery and its left and right branch vessels.

5 Post-processed view of the 4D Flow coronal slab after cropping and angulation orientated to the 4-chamber view of the heart: Pathlines demonstrate flow during ventricular diastole. Note the passive filling of the ventricles, with flow leaving the atria and crossing the atrio-ventricular valves.
As simple as possible, but no more

For planning, our technologists and physicians would routinely have to evaluate three independent parameters during planning. Since it was agreed that the FOV was to not be changed and that the 20% phase oversampling was acceptable for most patients’ habitus, the technologist was primarily responsible for modifying slice thickness of the 4D Flow acquisition. We agreed that a slice thickness of 2.5 mm in the anteroposterior direction would be optimum in order to balance appropriate coverage, image acquisition time, and spatial resolution. To ensure appropriate coverage for larger patients, we advised our technologist to increase slice thickness in increments of 0.1 mm and to use 3.0 mm as a maximum slice thickness with the caveat that slice thickness could also be slightly increased if times became unacceptably long (our goal is ~10 minutes). Velocity encoding was the second parameter that required planning prior to image acquisition. While the variety of valvular and stenosis-related pathologies can be expected to extend across a spectrum of different flow ranges, we elected to encourage a velocity encoding of 150 cm/s for patients undergoing routine evaluation, and 300 cm/s for patients with a known or highly suspected history of significant stenosis. Although our group considered a velocity-encoding scout, our goal was to be able to uniformly evaluate multiple types of pathologies. The need for multiple phase-encoding scouts for the various pathologies (e.g., aortic disease vs. pulmonary disease) would therefore be counter to our objective, so this option was not pursued. In our experience, the two settings for velocity encoding have succeeded in the majority of cases. In more severe cases of stenosis, alias unwrapping using our post-processing software was able to correct the problem. The third parameter that the technologist had to set for sequence planning was the flip angle. Since not all of our cardiovascular cases would require intravenous admin-

Compressed Sensing working overtime

Compressed Sensing (CS) retrospective ECG-gated 4D Flow has been a very promising approach for faster acquisition of this pulse sequence, which can often take approximately 12 minutes to acquire. With CS, it was expected that we could reduce our 4D Flow acquisition time approximately by half, allowing for faster patient turnaround, given that it is customarily run as the last sequence in our protocols. While our CS sequence does reduce acquisition time, it was found to require a significant amount of inline reconstruction on the scanner workstation. While the GPU provided with the MAGNETOM Sola scanner was able to provide an acceptable inline sequence construction time of approximately six minutes, the GPU of our older MAGNETOM Aera unit took longer and was found to not be acceptable. From a workflow perspective, we found that despite the differences in GPU capabilities on the MAGNETOM Sola and Aera platforms, the average was approximately 12 minutes from the start of the sequence acquisition to the completion of the inline reconstruction. While the shorter acquisition time provided by CS was felt to be better for the patient, since the scan would be completed about six minutes earlier, there is also still some debate as to how phase-contrast data fidelity is impacted by aggressive acceleration techniques. Therefore, we have so far opted to not utilize CS approaches in favor of acquisition and data uniformity across all scanner platforms.
9 Cardiac MRI performed for quantification of pulmonary-to-systemic flow ratio (Qp:Qs): (9A) A secundum atrial septal defect is shown in the four-chamber view (yellow arrow); (9B) a double-oblique imaging plane is placed above the aortic valve, and the region of interest is traced throughout the cardiac cycle to obtain a flow-time curve and Qs quantification; (9C) 4D Flow visualization shows high velocity flow transiting the aorta from early to late systole (left to right) with visualization of the left-to-right intracardiac shunt across the atrial septal defect (yellow arrow) during latter systole. In this case, Qp:Qs calculated by 4D Flow was 1.8, indicating hemodynamic significance.

8 Post-processing of 4D Flow data: (8A) Raw data is displayed in post-processing software and (8B) initial segmentation of the acquired image.
Making a diagnosis

One of the most important aspects of CMR is the ability to accurately quantify cardiac and valvular function, and, at least at our institution, there is now increasing demand for comprehensive aortic hemodynamic evaluation. As 4D Flow has become increasingly available, many software vendors now provide tools to post-process the data, generate 3D cine flow images, and perform flow quantification by placing 2D planes orthogonal to flow features of interest. Usually, some degree of background offset correction, eddy current correction, and occasionally anti-aliasing are required, and different software vendors address these needs in different ways. Once the data is ready for visualization, we often begin by reviewing velocity maximum intensity projections (for example, Fig. 9C), which allow for bulk flow visualization that can be helpful for plane placement and visualization of intracardiac and valvular jets. For most cases, it is best practice to evaluate flow through the aortic valve and main pulmonary artery, which allows for comparison with right and left ventricular stroke volume, and to validate internal consistency in the flow data. Research has shown [1] that flow quantification accuracy can be limited by areas of increased vorticity, which is why we often use streamline visualization (Fig. 10B) to identify areas of flow complexity that may impact quantification prior to final analysis plane placement.

We have multiple examples of 4D Flow “saving” our flow and velocity quantification in cases of poor 2D plane selection. Moreover, the ability to retrospectively analyze all the major vasculature in the chest, including pulmonary and systemic veins, provides multiple opportunities to check for internal consistency and to more accurately quantify valvular insufficiency or shunts (Fig. 9).

As adult congenital heart disease has become an increasing part of our practice, it is clear that the 4D Flow is far superior for flow quantification from an efficiency standpoint for these patients. For example, a repaired Tetralogy of Fallot patient might require 2D phase contrast imaging at the aortic valve, pulmonic valve, and left and right pulmonary arteries, which all require specialized planning sequences and expertise in vascular anatomy. 4D Flow in a coronal slab brings this acquisition much closer to being a “one-click” solution. We also have a large bicuspid aortic valve clinical service, so we tend to encounter many patients with aortic coarctation or repaired coarctations (Fig. 10). 2D plane placement on

![3D streamlines allow visualization of velocities in the aorta: (10A) 3D reconstruction of the thoracic aorta in a patient with bicuspid aortic valve and coarctation with (10B) streamlines showing helical flow patterns (white arrow) and flow acceleration at the coarct (yellow arrow) during early to late systole (left to right); (10C) 3D reconstruction of the thoracic aorta in a separate patient after coarctation repair, with (10D) now smoother streamlines indicative of substantial normalization of flow and shear stress during early to late systole (left to right).](image)
the scanner for evaluation of a tortuous coarctation can be particularly challenging, but 4D Flow makes the acquisition straightforward.

**Conclusions**

We have designed and implemented a clinical 4D Flow protocol for vascular flow evaluation with CMR that functions across multiple scanner platforms from Siemens Healthineers and is easy to perform for CMR technologists of all experience levels. Anecdotally, we believe this approach improves the patient experience and also provides the interpreting physicians with more consistent data for visualization and quantification. Moreover, this addition to our protocol not only allows for routine flow and velocity measurements of the great vessels at multiple sites, but also creates opportunities for advanced analysis such as aorta wall-shear stress and pulse wave velocity measurements, direct mitral valve flow quantification, and flow stasis mapping in the left atrium and false lumen of aortic dissection. These are currently under investigation and may become important diagnostic tools in the near future.

**Reference**


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**Contact**

Ryan J. Avery, M.D.
Associate Professor of Radiology (Nuclear Medicine)
Northwestern University
NMH/Arkes Family Pavilion Suite 800
676 N Saint Clair
Chicago, IL 60611
USA
ravery@northwestern.edu

Bradley D. Allen, M.D., M.S.
Assistant Professor of Radiology (Chest Imaging and Cardiovascular Imaging)
Northwestern University
NMH/Arkes Family Pavilion Suite 800
676 N Saint Clair
Chicago, IL 60611
USA
bdallen@northwestern.edu