Sunrise Session CV-4D-Flow: Ready for Primetime?
"4D-Flow: How it Benefits Patients"
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Target Audience: Physicians and Physicists interested in the clinical application of MRI for non-invasive evaluation of cardiovascular disease.

Background: Time resolved 3D phase contrast velocity MR angiography techniques, also known as "4D-flow MRI" is an emerging quantitative MRI method that has shown tremendous promise for the evaluation of a variety of diseases. These techniques have been applied with tremendous success for the evaluation of diseases of the aorta, cardiac valves, as well as congenital heart disease. Emerging applications include the evaluation of vascular disease in the abdomen including mesenteric ischemia, portal hypertension and the evaluation of renovascular disease. In addition, evaluation of intracranial neurovascular disease including the hemodynamics of aneurysms, arterial venous malformations and intracranial dissection and atherosclerotic disease has also shown tremendous promise.

Despite the tremendous advances and the promises of 4D flow to improve patient care, the paradigms in which 4D flow MRI can benefit patients are rapidly emerging. How does 4D flow benefit patients, in comparison to other vascular imaging techniques such as computed tomography angiography (CTA) or conventional MR angiography? How does it improve care relative to conventional 2D phase velocity MRI? Do the enormous size of these datasets and the complexity of the post processing justify potential improvements in clinical care? In this talk we will explore some of the potential benefits of 4D flow MRI and focus on examples in congenital heart disease and emerging applications in the abdomen. The workflow that is required to integrate 4D flow MRI into clinical care will also be reviewed.

Acquisition: Patients benefit from 4D flow MRI at multiple levels, starting with the acquisition. Emerging methods can acquire volumetric comprehensive 4D flow datasets within 5-15 minutes, depending on the specific application and the prescribed volumetric coverage and temporal/spatial resolution. Using free-breathing techniques, it is relatively simple to acquire comprehensive flow data in a large anatomical region, such as the chest or the abdomen. Using 2D phase velocity MRI, it is simply not feasible to interrogate all of the affected anatomy in a reasonable scan time. For example, patients with "total cavopulmonary connection" (ie; Glenn/Fontan repair) require flow measurements in double oblique planes at the following locations: IVC, SVC, left pulmonary artery, right pulmonary artery, aorta, and optimally both during inspiration and expiration. A comprehensive set of 2D phase velocity images to measure flow at these locations is very tedious and requires the presence of a physician at the scanner. Using volumetric 4D flow MRI, however, a technologist can acquire a single volumetric dataset without supervision. This obviates the need for a physician to be at the scanner, and most importantly minimizes the overall scan time for the patient. This has important safety indications for children who may require general anesthesia for these studies. In many cases, feeding and swaddling young children is sufficient and often very successful.

Emerging applications in the abdomen also show tremendous benefit by acquiring a comprehensive dataset in an area with very complex vascular anatomy. For example, comprehensive vascular evaluation of the abdomen may require interrogation of flow within the abdominal aorta, celiac axis, splenic artery, hepatic artery, superior mesenteric artery, left and right renal arteries, superior mesenteric vein, splenic vein, inferior mesenteric vein, main portal vein, and left and right portal veins. It is neither practical nor feasible to provide a comprehensive set of double-obique 2D phase velocity images through all of these vessels. All of these vessels can be interrogated accurately with a single large 4D flow dataset.

Additional Information: In addition to acquiring a comprehensive volumetric dataset in a relatively short scan time, the ability to acquire a time-resolved velocity vector field over the anatomy of interest provides a substantially more information than is available from 2D phase contrast imaging and contrast enhanced MRA or CTA alone. Complex difference image reconstructions generated from 4D flow data provide high resolution anatomical visualization of the vascularity. 4D flow also provides quantitative velocity measurements throughout the entire volume, opening entire new avenues for comprehensive hemodynamic evaluation.

In addition to flow and velocity measurements that can be made using 2D phase velocity imaging, the time resolved 3D nature of the velocity information provided with 4D flow MRI allows for measurement of other hemodynamic parameters including wall shear stress, and trans-stenotic pressure gradients. Other important hemodynamic parameters include kinetic energy, vorticity, and helicity are also easily generated using 4D flow MRI. In our practice, flow and trans-stenotic pressure gradients are the most commonly used quantitative parameters.

Further, 4D MRI allows for accurate visualization of flow patterns including flow directions. For example, the simple visualization of reversed flow in the coronary vein feeding gastroesophageal varices is all the information needed by a surgeon treating a patient with portal hypertension requires and will guide treatment of bleeding varices.

Perhaps more important is the ability of 4D flow MRI to provide longitudinal hemodynamic quantification, which is a critical part of treatment monitoring. Accurate treatment monitoring requires highly repeatable measurements at the same anatomical location. Since 2D phase velocity imaging is limited to specific double oblique sections that are ***prospectively*** selected, it may be difficult to reproduce the exact location on subsequent exams. With volumetric information, 4D flow MRI allows for more repeatable measurements at the same anatomical location, improving the precision of repeated measurements over time. In addition to improving patient care, this has important implications for hemodynamic measurements made as part of a clinical trial designed at evaluating new therapies, where hemodynamic parameters assessed with MRI are used as surrogate endpoints for treatment efficacy.

Visualization: We have found that the ability of 4D flow to visualize flow patterns such as vorticity, reversal of flow and flow acceleration has tremendous value for referring physicians. It is difficult to provide this information using other techniques including 2D phase velocity MRI. Through advanced visualization techniques that are commonly used with 4D flow including streamlines and particle traces, a tremendous amount of information can be conveyed to referring physicians using relatively small number of images. In this way, “a picture is worth a thousand word”. In our experience, this has been of tremendous value to our referring physicians who include general surgeons, vascular surgeons, transplant surgeons, hepatologists, neurologists, neurosurgeons and interventional radiologists. Further, referring physicians use these visualization methods to review studies with their patients and find these pictures to be remarkably helpful.

Workflow: At our institution, we have successfully integrated the use of 4D flow MRI into our clinical practice. Currently we use a time resolved phase contrast 3D radial method known as Vastly undersampled Isotropic PRojection reconstruction, or “PC-VIPR”. Other volumetric technique using

Cartesian 4D flow MRI techniques are also highly effective. Dedicated PC-VIPR pre-loaded protocols are installed on all of our magnets with parameters that specific to certain areas of anatomy including preset V_{enc} settings. This allows for simple protocoling and unsupervised acquisition of 4D flow MRI. Complex difference images are automatically reconstructed and are included automatically with the study sent to PACS.

Next, one of the physicists on our team is notified and time resolved raw image reconstruction is performed. Direct communication between the physicists and the radiologist is undertaken to focus the specific clinical questions. This is a critical step, because evaluation of 4D flow MRI images contains such a rich and large amount of information. Addressing a specific question is essential. Once the clinical question has been communicated understood, reconstruction of specific areas of anatomy and quantitative measurements are made. Occasionally, this is an iterative process, because unsuspected pathology may be discovered, and additional measurements are needed. This also requires relative close communication between the physicist to the radiologist to discuss and review images. Once the final evaluation has been made, final flow visualization images are then made in DICOM format and sent to PACS, including quantitative flow and pressure gradient measurements. The referring physician can create movies by playing DICOM images in CINE mode on the PACS. The ability to upload DICOM images into PACS has been a critical step in the implementation and success of our clinical 4D flow MRI program. Based on this workflow, we provide a turnaround time of less than 24 hours, but most often, image reconstruction with visualization and quantitative flow measurements are provided and reported on the same day as the exam. Finally, a major reason for this success has been an excellent partnership with our hospital, which recognizes the added value and benefit to our patients, and provides limited financial support to ensure the feasibility of this program.

Summary: Emerging applications of 4D flow MRI in multiple areas of the body can lead to improved patient care. These methods provide volumetric, comprehensive hemodynamic assessment in a relatively short scan time (5-15 minutes), avoiding the need to perform complicated and lengthy scans or repeated scans. This minimizes the need for general anesthesia in small children and obviates the need for a physician to monitor exams. Since the measurements cover the entire anatomy this facilitates highly repeatable measurements, which is critical for treatment monitoring during longitudinal follow-up. Finally, advanced visualization using a limited number of time resolved flow visualization diagrams can convey a tremendous amount of information both to referring physicians and patients leading to increased confidence in the characterization of important cardiovascular diseases.