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Rapid Comprehensive Evaluation of Luminography and Hemodynamic Function with 3D Radially Undersampled Phase Contrast Imaging MRI

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***Abstract*—Quantitative flow measurements with volumetric coverage and three directional flow encoding are technically feasible with magnetic resonance imaging yet prohibitively long in clinical settings. Data reconstruction from three dimensional angular undersampled MR acquisitions allows for dramatic reductions in scan time with tolerable imaging artifacts in many clinical applications. This approach provides high spatial resolution suitable for hemodynamic analysis in smaller vessels such as the renal artery, thereby providing additional crucial diagnostic information in a non invasive fashion. In an animal model, transstenotic pressure gradient measurements obtained with the novel acquisition scheme compared favorably with invasive intra arterial measurements (r = 0.977; 95% CI: 0.931-0.998; p < 0.001). In addition, human studies demonstrate the suitability of the technique for lumen measurements as an alternative for contrast enhanced MR Angiography and the associated risks with the use of an external contrast agent in certain patient populations.**

I. Introduction

MAGNETIC Resonance Imaging (MRI) is routinely used in the non-invasive evaluation of cardiovascular disease. In addition to providing morphological information such as the patency and vessels, quantitative flow measurements can be obtained with velocity sensitive encoding techniques [1]. This approach, referred to as phase contrast (PC) MRI, is commonly used in clinical applications such as the evaluation of valve disease [2]. However, the extensive scan time for PC MR acquisitions have limited their use to one directional velocity mapping of a single slice to be completed in a single breath hold.

Only recent advances in MR hardware design, particularly more powerful gradient systems and the use of parallel imaging techniques have permitted the use of three directional PC MR with volumetric coverage in broader human studies because of the extensive scan time associated with multi-directional velocity encoding, respiratory and cardiac gating, and volumetric acquisitions. These studies have mainly focused on the largest vessel in the human body, the aorta, because of the necessary compromises in spatial resolution to limit the scan time to below 15-20 min [3].

We recently developed a sampling scheme VIPR, Vastly Undersampled Isotropic Projection Reconstruction [4], that acquires MR data on 3D radial lines covering a sphere in the acquisition space, frequently referred to as k-space. In contrast to the traditional rectilinear sampling patterns, radial sampling allows for significant data undersampling below the Nyquist limit with tolerable artefacts in many applications if the image has high contrast and is relatively sparse. PC MRA data are well suited for such data undersampling schemes because of their sparsity from the inherent subtraction process in the reconstruction, providing high signal from the vessels and only small contributions from the background signal.

Here we describe our results for the adaptation of the 3D radial trajectory for phase contrast imaging, PC VIPR [5], in various clinical applications. This approach provides significantly higher spatial resolutions as compared with traditional MR acquisitions allowing both the visualization and hemodynamic analysis of small vessels. The increased resolution makes PC VIPR a viable alternative for high resolution MR Angiography in patients in which the standard contrast enhanced MR angiography (CE MRA) is contraindicated due to risk associated with nephrogenic systemic fibrosis (NSF) [6] and improves the ability to quantify hemodynamic derivatives, such as relative pressure, from the velocity data.

II. Materials and Methods

The sequence was implemented on clinical 1.5 T and 3 T systems (GE Healthcare, Waukesha, WI). The radial k-space

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data were interpolated onto a Cartesian sampling grid with a Kaiser Bessel interpolation kernel for rapid reconstruction via 3D Fourier transform [7]. To reliably achieve high quality images, several correction schemes were applied to account for the effects of trajectory errors, motion, and aliasing associated with undersampling [8]. The PC VIPR data were reconstructed as magnitude images, velocity vector fields, and angiograms calculated from the magnitude and velocity images.

A. Lumenography

To evaluate the performance of PC VIPR as a non-contrast enhanced MRA (NCE MRA) method, a human study was conducted with respiratory gating and retrospective ECG gating for renal artery stenosis in patients with suspected atherosclerotic disease or post-operative renal transplant. Using a protocol approved by the institutional review board, twelve healthy volunteers and 51 patients (14 transplant, 37 native suspected renal artery stenosis) were imaged with a product, ungated 3D PC sequence and PC VIPR. The scan duration for a PC VIPR scan was 10 min and provided an angiogram and cardiac phase resolved velocity vector fields for a large FOV (32x32x16cm) with isotropic spatial resolution (1.2x1.2x1.2 mm. In cases where contrast agent use was not contraindicated, CE MRA exams (29 cases) were also acquired. The images were evaluated in terms of quality and visibility of vessels. 2 blinded radiologists compared vessel visibility in 220 paired vessel segments acquired with CE MRA and PC VIPR independently and in random order. The scoring scale was defined as 0=non diagnostic to 4 = excellent, all scores reported as medians.

B. Trans Stenotic Pressure Gradients (TSPG)

Following Animal Care and Use Committee protocol approval, bilateral renal artery stenosis (RAS) was surgically created in 12 swine. All studies were performed under general anesthesia. The PC VIPR sequence (dual echo, 18,000 projection angles, 10˚ flip, TR/TE (first echo) = 11.4/3.7 msec, BW = 62.5kHz, imaging volume: 260x260x160 mm3, isotropic spatial resolution: 1x1x1 mm3, venc = 150cm/s, scan time 11:00 min) was performed without the application of an intravenous contrast agent. Respiratory gating was performed with an adaptive gating scheme based on bellows readings with 50% respiratory gating efficiency. Pressure gradients were calculated using the Navier-Stokes equation and an iterative algorithm that has been described elsewhere [9, 10]. Endovascular pressure measurements made with a guidewire were used as the gold standard for quantification of the TSPG (Certus Pressure Wire, RADI, Uppsala, Sweden). The DSA and MRI TSPG measurements were performed using a combined MRI/angio suite that ensured short delay times between the two measurements. Pearson correlation coefficients were calculated to determine the similarity between the two pressure measurements.

C. Congenital Heart Disease

MR Lumenography and sequential 2D, one directional velocity measurements are frequently performed in the follow ups of patients with congenital heart disease. Therefore, the availability of that information from a single scan with oblique reformatting capabilities with isotropic spatial resolution and additional hemodynamic parameters offers several benefits. Twenty consecutive CHD patients with a variety of pathology including aortic coarctation, Scimitar syndrome, double inlet left ventricle, and atrial septal defects, among others were scanned at 1.5T and 3 T after obtaining patient consent according to our IRB protocol. Typical scan parameters were: imaging volume = 320 x 320 x 180 mm3, readout = 256-320, (1.0-1.25 mm)3 acquired isotropic spatial resolution, VENC of 50-150 cm/s (application specific), TR/TE = 8.7/2.8, flip = 10º Cardiac gating was performed retrospectively with a temporal filter for radial acquisitions [11], similar to view sharing in Fourier sampling. Respiratory gating was implemented with an adaptive gating scheme based on bellows readings, resulting in a scan time of approx 10 min with 50% respiratory gating efficiency. CE-MRA were used for comparisons when available.

III. Results

A. Lumenography

Both readers reported equivalent overall image quality for CE MRA and PC VIPR (4 for all exams). One reader scored the vessel visibility of the segmental renal arteries higher for

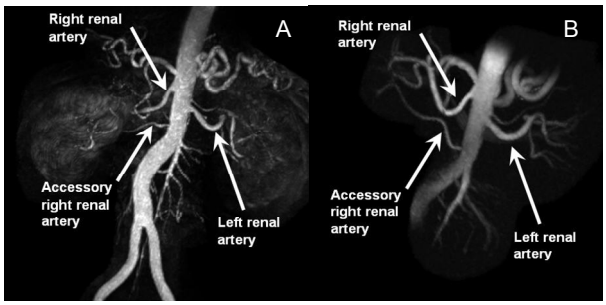

Fig. 1. Example of a angiogram calculated from the magnitude and velocity images of a PC VIPR scan. 62 year-old male with hypertension and suspected renal artery stenosis. The PC VIPR angiogram acquired without a contrast agent and derived from magnitude and phase information (B) compares favorably with the CE MRA exam acquired with a gadolinium based bolus(A).

PC VIPR (4) than for CE MRA (3) while the other reader scored them equivalent (3 for both). While some CE MRA scans had compromised quality because of poor breathholds, some PC VIPR exams had reduced image quality in highly obese patients. Figure 1 shows both angiograms from a patient.

B. Trans Stenotic Pressure Gradients

In 5 cases of severe RAS (mean stenosis - 86%), the residual lumen within the stenosis was so small that TSPG

could not be determined using PC VIPR since pressure differences can only be calculated for connected regions. These lesions were excluded from the statistical analysis. However, the angiographic reformats from those data readily revealed severe, hemodynamically significant RAS. The renal arteries distal to the stenosis could still be visualized except in the one case of an occlusion. In the 19 renal artery stenoses that allowed for TSPG analysis (mean 62%) excellent correlation between the non-invasive TSPG utilizing PC VIPR and endovascular pressure measurements was found ($r = 0.977$; 95% CI: 0.931, 0.998; $p < 0.001$). Figure 2 demonstrates such an example. The severity of stenosis based on visual assessment of the images also correlated well with DSA (Pearson $r = 0.77$).

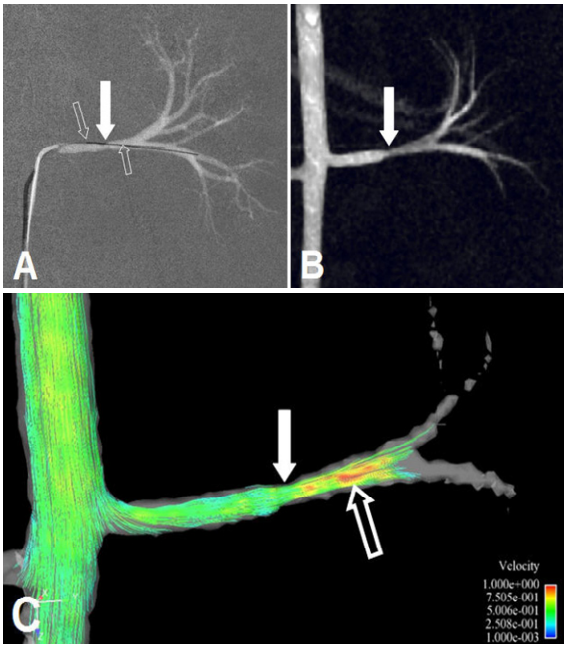

Fig. 2. Moderate renal artery stenosis in swine model: The roadmap image of the DSA exam (A) shows two endovascular pressure sensing guidewires (light arrows in A indicate location of pressure sensors) across a moderate left renal artery stenosis (solid arrow in A). A maximum intensity projection (MIP) image (B) and streamline visualization (C) of non contrast enhanced PC VIPR MRA readily reveal the stenosis (arrows in B, C) and increased velocity distal to the stenosis (open arrow C).

C. *Congenital Heart Disease*

PC VIPR data sets were successfully acquired in all patients. MR angiograms were created in order to visualize cardiovascular structures and to define the vessel boundaries for the derivations of additional hemodynamic parameters directly from the velocity fields. All anatomical structures visualized on CE MRA images were identified on PC VIPR images. This includes a 2 year-old with pulmonary venolobar (Scimitar) syndrome with an anomalous pulmonary venous return to the SVC and IVC, in addition to an anomalous systemic artery. The cardiac gated data were used for advanced hemodynamic analysis. For example, Fig. 3 a-d shows the hemodynamic analysis for an 18 month old boy with an aortic coarctation. The velocity fields (Fig. 3a) and pressure difference map (Fig. 3b) show changes over the vessel narrowing using advanced visualization software (Ensight, CEI, Apex). The pressure difference as measured over the coarctation was found to be 12 mmHg with Navier Stokes equations applied to the velocity fields. These measurements indicate a mild coarctation as was concluded from the anatomical assessment.

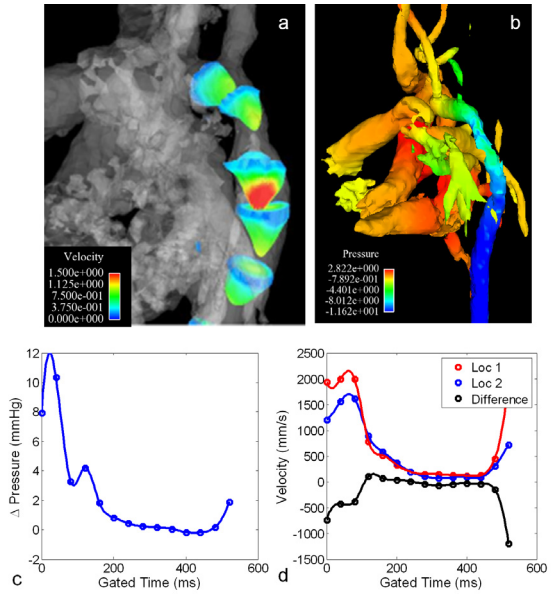

Fig. 3. Hemodynamic analysis for a patient with aortic coarctation. (a) Flow velocity profiles showing the highest velocity immediately distal to the coarcation. (b) Pressure difference map showingthe drop over the coarctation. Pressure difference (c) and velocity (d) measurements over the coarctation as a function of time within the cardiac cycle (peripheral gating).

IV. Conclusion

The human renal artery study demonstrated that PC VIPR acquisitions provide renal angiograms of good quality. It has become the standard protocol at our institution for imaging patients who can not receive Gd (risk for nephrogenic systemic fibrosis – NSF), including all transplant patients.

In addition, PC VIPR can be used to provide non-invasive transstenotic pressure gradient measurements as demonstrated in the animal model. This approach demonstrated excellent correlation between TSPG measurements by PC VIPR and endovascular guide wires. It has the potential to become a major advance in the noninvasive evaluation of RAS and, as a result, in the management of renal hypertension. In an ongoing study we investigate the correlation of trans-stenotic pressure gradients obtained non-invasively with PC VIPR and invasively under X-ray fluoroscopy in humans.

Comprehensive anatomical and functional cardiovascular MRI of congenital heart disease can be performed using PC

VIPR, providing a powerful new tool for non-invasive diagnosis in congenital heart disease. The spatial and temporal resolution required for such post processing are only feasible with dramatic data undersampling to maintain a clinically feasible scan duration. Future patient studies will investigate the clinical significance of the hemodynamic parameters such as wall shear stress and pressure gradients for various pathologies.

In summary, PC VIPR can offer parameters for the assessment of cardiovascular disease derived directly from the mapping of volumetric cine velocity fields in addition top providing MR angiograms simultaneously. These non-invasive measurements could prove beneficial in several applications including, but not limited to aneurysms, stenosis, dissections, pulmonary hypertension, and congenital heart disease.

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