Renal Blood Flow Measurement by Breath-hold Phase-Velocity MRI: A Validation Study

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Introduction

Phase contrast MRI (PC-MRI) methods for direct measurement of blood flow have been investigated since early stages of MRI, but have limited clinical application to date. Blood flow to the kidneys is an important parameter in characterization and quantification of kidney function. Indeed, measurement of renal arterial blood flow (RBF) by ciné PC-MRI is considered an important application for evaluation of a variety of kidney disorders, but has been technically challenging. Early studies using ciné imaging methods in the early 1990s reported promising results but also flagged need for improvement in speed, resolution, motion compensation, and signal-to-noise ratio (SNR). Technical innovations since then include fast imaging methods which, coupled with improved gradients, now allow high-resolution breath-held imaging. In addition, phased-array coils have improved SNR, better flow analysis software enables efficient flow analysis with phase correction, and improvements in angiographic imaging offer enhanced scouting of oblique flow planes.

Earlier studies on reliability of methods dated from before most recent improvements, and reported encouraging correlations with other methods like ultrasound probes in animals or clearance methods, but provided less than definitive answers to questions of overall accuracy and reproducibility. The purpose of the present study is validation of current technique, i.e., including all above-mentioned innovations, to test maturity of the technology for more widespread incorporation of RBF mapping in clinical renal MRI. This effort is an initiative of the NIH-sponsored Consortium for Radiologic Imaging Studies in Polycystic Kidney Disease (CRISP) monitor progression of Polycystic Kidney Disease (PKD).

Earlier work in this project reported inter- and intra-rater variability statistics in analysis of RBF measurement using the same MRI methods as described below, with favorable average coefficients of variation (CV, defined as standard deviation divided by mean value) of 1.3% and 2.5% respectively[2]. The present report addresses additional specific parameters defining accuracy and reproducibility of the method, in an effort to arrive at a comprehensive evaluation of the state of the art. These parameters aim to characterize (1) overall accuracy of the method, (2) reproducibility of the overall imaging experiment *in-vivo*, in relation to (3) the short-term physiological stability of the RBF quantifier itself.

Materials and Methods

The breath-hold RBF imaging protocol is used with similar protocols on different 1.5T vendor platforms at two CRISP sites (Mayo: GE Signa R9, Emory: Philips Intera R8/R10). Validation was performed by phantom imaging studies and by repeated flow imaging procedures on healthy volunteer subjects, all acquired on the Philips equipment. Imaging parameters of the gradient echo cine-PC sequence are: TR=27ms, TE=11ms, flip angle 35 degrees, 14-20 phases/cardiac cycle depending on heart rate, no view sharing, prospective or retrospective VCG synchronization. Images were acquired with 192 or more phase encodings on a square FOV of 200 mm, reconstructed at 256x256 pixels, at imaging times of 20-35 s, depending on heart rate, and standard velocity encoding of 100 cm/sec maximum, adjusted to 150 cm/sec when velocity wraparound is observed.

Accuracy assessments were obtained using a flow loop connected to a vessel lumen phantom constructed from poly-vinyl alcohol with six (steady flow) or seven (pulsatile flow) straight flow channels of different diameters spanning the range reported in literature (2-11mm) of adult renal arteries (RA), with realistic range of flow rates for each diameter (cumulative range: 100-1200 ml/min). Measurements of steady flow and pulsatile flow, programmed with RA flow waveform on a CF1000MR pump (Shelley, Inc. , Toronto) with simulated cardiac synchronization, were compared with reference measurements from 1-minute fluid collection before and after MRI.

Reproducibility and stability of RBF mapping were tested using four repeat MRI studies, each following a 12-hour fasting period, at weekly intervals, on six volunteers, 4 male and 2 female, ages 24-39 without known current or past kidney problems and with normal serum creatinine levels, after informed consent. Left and right RBF flow planes were scouted and imaged twice, followed by repeat scouting and again imaging twice on one side, which was alternated across weeks. Gd-DTPA was injected, and this RBF protocol was repeated after a 10-minute delay to model post-contrast RBF measurement after angiographic or perfusion imaging.

All flow analysis was performed by the same analyst using FLOW software V3.0 (Medis, Inc., Leiden, The Netherlands). RBF is calculated by integrating pixel velocities across semi-automatically edited vessel cross-sections to yield vessel flux values at each time point, then integrating time flux values across the cardiac cycle to yield flow per heart beat, and finally multiplication by the heart rate to give total flow per minute.

Results

Bland-Altman analysis for 6 combined vessel diameters (3.3-11.1 mm) on steady flow data in a PVA phantom resulted in 95%-confidence limits of agreement between MRI and fluid collection within an interval of [-66.25,72.34] ml/min over the entire flow range of 200-1200 ml/min. Regression analysis found y=0.95x+29.3 ml/min (y=MRI flow, x=fluid collection) with R^2=0.988.

For pulsatile flow through a PVA phantom the Bland-Altman analysis for 7 combined vessel diameters (2.1-11.1 mm) resulted in 95%-confidence limits of agreement between MRI and fluid collection within an interval of [-53.2,36.2] ml/min over the entire range of 50-1200 ml/min. Regression analysis found y=0.98x+1.8 ml/min (y=MRI flow, x=fluid collection) with R^2=0.993.

In the six volunteers we found mean renal flow values in the range 497-619 ml/min on the left and 511-627 ml/min on the right. Immediate repetition of a flow scan showed a standard deviation of 17.5 ml/min on average, corresponding to a mean CV of 2.9%. Repetition of the scan including the plane scouting process showed a standard deviation of 34.2 ml/min on average, corresponding to a mean CV of 6.0%. Averaged flow in the same kidney varied among weekly repeat sessions with standard deviations averaging 44.5 ml/min and CV of 7.9%. In the same session, the average standard deviation in all pre-contrast scans of the same kidney was 24.3 ml/min, compared to 25.5 ml/min for post-contrast. The mean post-contrast flow was on average 6.64 ml/min higher than pre-contrast flow.

Discussion and Conclusions

Our results suggest that current MRI technology allows accurate and reliable quantitative imaging of renal blood flow in breath-hold mode. Phantom experiments demonstrate highly accurate results, with a corresponding average CV of about 3%, for simulated renal arteries greater than 3mm in diameter. Repeat *in-vivo* scans on volunteers are consistent with these findings but suggest that careful flow plane scouting is important for reproducible results. Important criteria in this respect are placement of the RA flow plane (1) sufficiently distal to the branch from the aorta to avoid QF contamination by aortic flow, and (2) sufficiently proximal to possible early branches; in difficult cases additional angiographic scouts are recommended. Renal flow under moderately controlled physiological conditions in normal subjects appears stable within comparable limits within the study's three-week time frame. Our results also suggest that the use of Gd-DTPA contrast agent does not change flow or improve reproducibility in healthy subjects.

References

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