Velocity Unwrap for High Resolution Slice-Selective Fourier Velocity Encoding Using Spiral SENSE

Jennifer Anne Steeden[1], Alexander Jones[1], David Atkinson[2], Andrew M Taylor[1], and Vivek Muthurangu[1]
[1]UCL Institute of Cardiovascular Science, London, UK, United Kingdom, [2]Department of Medical Physics and Bioengineering, UCL, London, UK, United Kingdom

Introduction: Quantification of peak velocity (V_{max}) is important in the assessment of stenotic flow jets in patients with congenital heart disease (CHD). Unfortunately, phase-contrast MR (PCMR) tends to underestimate peak velocities and clinically Doppler ultrasound (US) is used as the reference standard for assessing stenoses. Slice-selective Fourier Velocity Encoding (FVE) can measure peak velocities in MRI, but is not commonly used due to long acquisition times. However, FVE is amenable to significant acceleration using parallel imaging (as well as other speed-up techniques). Therefore we have developed a high resolution, slice-selective FVE sequence that combines efficient spiral trajectories with sensitivity encoding (SENSE) in *kx-ky*, partial-Fourier acquisition in *kv* and a novel velocity-unwrap technique in *v*. The aim of this study is to validate this sequence in patients with CHD.

Methods: FVE was performed using a uniform-density spiral trajectory with 16 interleaves (table 1). Parallel imaging was applied (R=4) and reconstructed using an iterative SENSE algorithm[1]. Partial-Fourier was performed in *kv* (67%) with a homodyne reconstruction[2].

Velocity-unwrap: For a given pixel in a stenotic jet, velocities generally occupy one side of the velocity spectrum at any given time point due to the unidirectionality of flow. The lack of signal on one side of the velocity spectrum means that under sampling in *kv* will not immediately result in velocities being overlaid. In fact, up to two-times undersampling (equivalent to halving the velocity FOV) can be performed in *kv* without any risk of data being overlaid in *v*. Acquiring one additional *kv*-position with the full VENC, and reconstructing this using traditional PCMR provides information about the direction of flow (on a pixel-by-pixel, frame-by-frame basis). This allows accurate unfolding of velocity data.

	lr-PCMR	hr-PCMR	FVE_{21}	FVE_{41}
TE/TR (ms)	~2.2/5.0	~2.2/5.0	~2.5/9.3	~3.5/10.3
Readouts	Cartesian	Cartesian	Spiral: 16 interleaves	Spiral: 16 interleaves
Matrix Size	128	256	192	192
Image FOV (mm)	320	320	450	450
Acceleration (in *kx-ky*)	2(GRAPPA)	2(GRAPPA)	4(SENSE)	4(SENSE)
Partial Fourier (in *kv*)	-	-	67%	67%
Velocity unwrap	-	-	□	□
kv positions acquired	-	-	14	15
Reconstructed velocity levels	-	-	21	41
Scan Duration (heartbeats)	15	108	15	15
Spatial resolution (mm)	~2.5	~1.3	~2.3	~2.3
Temporal resolution (ms)	~40	~30	~37	~41
Velocity Resolution (cm/s)	-	-	30-75	18-38

Table 1: Imaging Parameters

In-vitro: A pulsatile flow pump was connected to a tube phantom (diameter 13mm) with a stenosis of 6mm. At 15 different flow rates, V_{max} was measured using; *1)* ultrasound (US), *2)* low-resolution PCMR (lr-PCMR), *3)* high-resolution PCMR (hr-PCMR), *4)* FVE with SENSE and partial-Fourier with 21 reconstructed velocities (FVE_{21}) and *5)* FVE with SENSE and partial-Fourier, plus velocity-unwrap giving 41 reconstructed velocities (FVE_{41}). SNR estimates were compared between FVE_{21} and FVE_{41}.

In-vivo: In 15 CHD patients with stenoses (9M:6F; 17±17years), V_{max} was assessed using US Doppler and the same PCMR and FVE sequences as in the *in-vitro* study.

Results: In-vitro: There were no statistically significant differences between V_{max} measured using US and FVE (table 2). However both PCMR sequences showed statistically significant underestimation of V_{max} compared to US. This is particularly true of lr-PCMR, which underestimated V_{max} by >0.5m/s.

In-vivo: As in-vitro, PCMR underestimated V_{max} with a clinically significant bias particularly when using lr-PCMR. There were no statistical differences between V_{max} measured using US and FVE sequences with excellent agreement on Bland Altman and correlation analysis. Figure 1 shows an example of the good agreement between the peak-flow profiles from Doppler US and the four MRI sequences, in one patient.

Conclusions: FVE allows more accurate assessment of V_{max} than PCMR as it measures a velocity spectrum per pixel, rather than the average velocity. We have demonstrated that it is possible to achieve high resolution FVE within a short breath-hold by combining spiral trajectories, parallel imaging, partial-Fourier and velocity-unwrap. This sequence was shown to be significantly more accurate than PCMR in-vitro and in-vivo. Furthermore using the novel velocity-unwrap technique there was a trend towards higher accuracy due to better velocity resolution. Thus, the sequence may be able to replace US in assessment of V_{max} in CHD.

	US	lr-PCMR	hr-PCMR	FVE_{21}	FVE_{41}
In-vitro					
Peak velocity (cm/s)	441±144	375±133 [a]	398±136 [a]	447±140	443±144
Bias (cm/s) *	-	-66	-42	7	3
Limits of agreement (cm/s) *	-	-26 to -105	-10 to -75	28 to -14	17 to -12
Correlation coefficient (r) *	-	0.9926 (*P*<0.0001)	0.9949 (*P*<0.0001)	0.9977 (*P*<0.0001)	0.9987 (*P*<0.0001)
Estimated SNR	-	-	-	5.2±2.6	5.7±4.1
In-vivo					
Peak velocity (cm/s)	258±77	225±71 [a]	226±61 [a]	254±81	254±82
Bias (cm/s) *	-	-33	-32	-4	-4
Limits of agreement (cm/s) *	-	70 to -135	60 to -124	73 to -80	59 to -67
Correlation coefficient (r) *	-	0.7634 (*P*=0.0009)	0.8000 (*P*=0.0003)	0.8833 (*P*<0.0001)	0.9223 (*P*<0.0001)

* Calculated with Doppler US
[a] Value is significantly different from US (*P*<0.05)

Table 2: In-vitro and In-vivo results

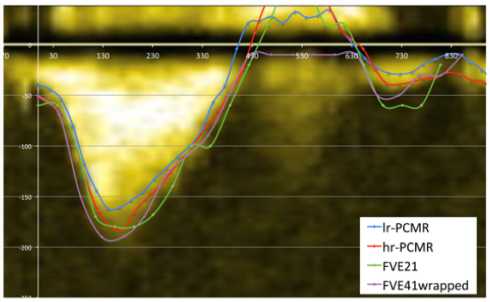

Figure 1: Resultant peak-flow profile from Doppler US (background) and MR over time in-vivo in one patient.

References:

1. Pruessmann KP, MRM 2001;46(4):638.
2. Noll DC, Medical Imaging, IEEE Transactions on 1991;10(2):154.