Undersampled Spirals for Real-time Flow Measurements

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Introduction: Measurement of great vessel flow is an important part of the diagnosis and management of patients with cardiac disease. Phase contrast MR provides an accurate, reproducible method of measuring flow, which has become an integral part of clinical assessment. In order to account for cardio-respiratory motion, flow is usually acquired using retrospective cardiac gating and multiple signal averages. However, this may be problematic in patients with irregular cardiac rhythms, and is time consuming. An alternative approach is to measure flow in real-time, which can be achieved through data undersampling and specialised reconstruction algorithms [1]. Spiral trajectories are a very time efficient method of traversing k-space and also have excellent flow properties [2]. Real-time spiral flow sequences using a SENSE reconstruction algorithm have previously been shown to be fast and accurate [3]. In this study we compare uniform and variable density spiral acquisition with SENSE and kt-SENSE reconstruction algorithms for real-time flow. Of these reconstructions, only kt-SENSE exploits spatiotemporal correlations within data. This may provide greater temporal resolution, through increased undersampling, or a more accurate reconstruction.

Method: We developed real-time, non-gated phase contrast spiral sequences with multiple interleaves. The coil sensitivities and training data required for the reconstruction algorithms are calculated from the acquired data, not from a separate scan. The user can control the density of the spiral interleaves, the acceleration factor (R), the velocity encoding (VENC) and the reconstruction algorithm. We compared a reference, gated sequence that reconstructs an average cardiac cycle (acquisition time ~4 minutes, depending on the RR interval of the subject) with:

- A uniformly sampled spiral sequence, reconstructed using SENSE (R=3, R=4)
- A variable density (vd) spiral sequence (100% sampling density from centre to 70% at the outer portion of k-space), reconstructed using SENSE (R=3, R=4)
- A variable density spiral sequence (300% for R=3, or 400% for R=4, sampling density from centre to 70% at the outer portion of k-space), reconstructed using kt-SENSE (R=3, R=4)

We acquired data from a pulsatile flow pump (Harvard Medical Systems) and also from the aorta of 2 free-breathing volunteers for the 7 different sequences described above. All experiments were performed on a 1.5T clinical scanner (Avanto, Siemens, Erlangen, Germany). Typical in-vivo sequence parameters for the spiral sequences were 128x128 matrix size, 450x450 mm FOV, 8mm slice thickness, 15^o flip angle, 12/R interleaves, 1450Hz/pixel BW, 220cm/s VENC, 1.45ms TE, with temporal resolution and spatial resolution shown in table 1. The reference data was acquired at the beginning of the scan, and the other scans were carried out in order from left to right across Table 1 – the time difference between the reference scan to the end of the scan was approximately 20 minutes. All reconstruction was done on the scanner and the DICOM data was segmented manually using the magnitude images and flows calculated using a custom built plugin for Osirix (Osirix Foundation, Geneva, Switzerland).

Results: The results are presented in Table 1:

	Reference (retrospectively gated)	**SENSE R=3**	**SENSE R=4**	**vd SENSE R=3**	**vd SENSE R=4**	**kt SENSE R=3**	**kt SENSE R=4**
Temporal resolution (*ms*)	Average RR / 30 (e.g. volunteer1: 32ms)	67.36	50.52	54.4	40.8	56.56	42.42
Spatial resolution (*mm*)	1.5 x 1.5 x 5.0	3.5 x 3.5 x 8.0	3.5 x 3.5 x 8.0	3.5 x 3.5 x 8.0	3.5 x 3.5 x 8.0	3.5 x 3.5 x 8.0	3.5 x 3.5 x 8.0
Flow pump (*L/min*)	3.4	2.7	2.6	2.8	2.7	3.0	3.2
Volunteer 1 (*L/min*)	4.3	3.9	4.2	4.2	3.8	4.4	4.2
Volunteer 2 (*L/min*)	4.6	4.1	4.0	4.2	4.0	3.8	3.8

Table 1: Comparison of temporal and spatial resolution for each of the sequences and flow values from the phantom and 2 volunteers.

For the pulsatile flow phantom, unlike the volunteers, the flow volume per cycle and the RR interval are fixed, therefore any differences in these results are expected to be from errors in the sequence or reconstruction. Compared to the reference scan, all of the sequences tested in this study underestimated the total flow volume. For the flow phantom, SENSE with 4-fold acceleration performed worst with flow volume of 2.6 *L/min* (error of -0.8 *L/min*) and kt-SENSE with 4-fold acceleration performed best with flow volume of 3.2 *L/min* (error of -0.2 *L/min*).

Results from the volunteer data also show a fluctuation compared to the reference. In this case it is difficult to separate variations due to sequence and reconstruction errors, from physiological changes due to anxiety or relaxation. Nevertheless the results are consistent to within 0.8 L/*min*, and the flow curves for a single cardiac cycle correlate well for all methods as seen in Figure 1a).

During this study we were also able to calculate the flow curves over many cardiac cycles, as shown in Figure 1b). The low frequency oscillation seen in the peaks of the data show that this real-time sequence allows the effect of breathing on cardiac output to be observed. It is not possible to observe this in the reference sequence as these variations are averaged out.

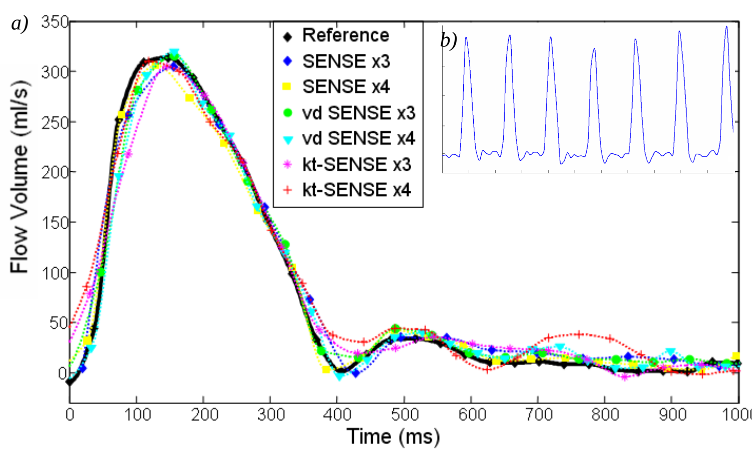

Figure 1 a) Real-time spiral flow curves for volunteer 1 from a single cardiac cycle for each of the methods, compared to the reference flow curve which is averaged over many cardiac cycles. b) Flow curve over many cardiac cycles from uniformly sampled spiral sequence, reconstructed using SENSE (R=3).

Discussion: Undersampled sequences trade SNR for improved temporal resolution and real-time capabilities. Spatial resolution is reduced in our spiral sequence due to a smaller matrix size and the need for a larger FOV to avoid wrapped tissue affecting the iterative reconstruction algorithms. Spiral sequences are also subject to trajectory and off-resonance errors that may create blurring. Nevertheless, the results presented here indicate that non-Cartesian SENSE and kt-SENSE can both be used effectively in measuring flow in real-time. We aim to use this sequence on patients in real-time applications, such as measuring flow during exercise, and on patients with arrhythmias.

References: [1] Pruessmann, MRM 46:638–651 (2001). [2] Nishimura, MRM 33:549-556 (1995). [3] Nezafat, MRM 54:1557–1561 (2005)