Scan time reduction for three-directional phase contrast sequences: a signal processing approach

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Introduction Three-directional phase contrast sequences for the measurement of flow velocities are gaining increasing popularity in the magnetic resonance research community. However, the high dimensionality of the data requires multiple acquisitions for velocity encoding and thus lengthy scan times. Therefore, the optimization of the scanning efficiency is crucial. The traditional phase contrast reconstruction method extracts a single velocity point from four acquisitions, yielding a final temporal resolution equal to four times the duration (TR) of a single encoding step. As shown previously in (2), the temporal resolution can be increased by a "sliding window" reconstruction or view sharing (3). However, significant distortions of the frequency content of the signal and thus underestimation of peak velocities and low pass filtering of temporal dynamics can still be present. In this work, we present a postprocessing method based on inverse signal filtering that can partially compensate for the distortion, thus effectively increasing the available bandwidth by a factor of two with respect to the conventional reconstruction, and therefore enabling an analogous decrease of the total acquisition time.

Theory Any three-directional phase contrast sequence implementing a "4-point balanced" acquisition scheme (1) acquires information about the velocity waveform on all axes for every encoding step, enabling a "sliding window" approach to the reconstruction. In order to obtain a signal with exactly the same number samples as the total number of encoding steps, an assumption of periodicity can be used, and steps from the first phase can be pooled with the ones from the last phases to reconstruct the missing samples. The resulting signal will still be a low-pass (LP) -filtered version of the original signal. The frequency components at normalized frequency F=0.5 completely cancel resulting in a significant distortion in the passband, the half-maximum bandwidth being at F=0.32, with a blunt transition. The effects of this filter can be compensated by applying an inverse filter to the reconstructed velocity signal. As the original LP filter has two zeros, a complete restoration of the signal is impossible, but the shape of the passband can be optimized up to the first zero of the filter at F=0.5. The order of the inverse filter can be larger than the actual number of acquired samples, because the filter weights can be initialized under the periodicity assumption.

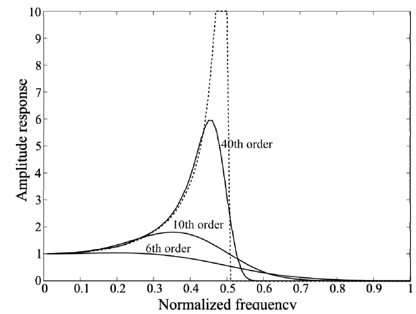

Fig. 1 Desired frequency response (dashed line) and responses of the designed filters

Materials and methods

Filter design. An inverse FIR filter was designed by means of a frequency sampling method. The desired response was defined based on the inverse of the frequency response of the original LP filter, clipped in order to have a maximum gain of 10, and to be zero for F $\geq$ 0.5. The gain at F=0 of the designed filters was constrained to be 1 in order to avoid changing the average value of the waveform. The filters were designed to have zero phase (non-causal filters). Filters of various orders (6, 10 and 40) were designed and compared, and their responses are shown in fig. 1.

Data acquisition. Internal carotid arteries of a healthy volunteer were scanned on a 3T whole-body MR scanner (Verio, Siemens Healthcare, Erlangen, Germany) with a photoplethysmograph (PPG)-gated custom phase contrast spoiled gradient echo sequence. The acquisition was run twice, the first time with high temporal resolution and through-plane encoding, in order to provide a fully-sampled reference scan, the second time it was run with a three-directional acquisition with a lower temporal resolution (undersampled scan). The first scan with single-direction velocity encoding had a TR of 7.6ms and was reconstructed with a conventional phase contrast algorithm, yielding a temporal resolution of 15.2ms. The second scan was performed by scanning 4 k-space lines per flow encoding step, yielding to a temporal resolution after sliding window reconstruction of 30.4ms (and equivalent to 121.6ms resolution of the conventional reconstruction). A 40th-order inverse filter was applied to the undersampled velocity waveform, and the filter weights were initialized using the assumption of periodicity of the velocity signal in order to avoid transient effects.

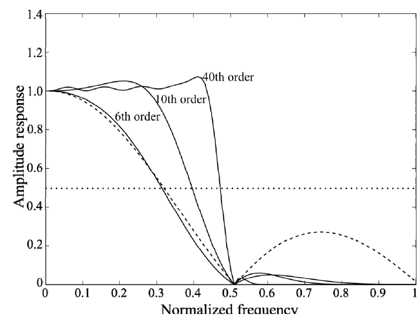

Fig. 2 Original frequency response (dashed line) and combined responses. The dotted horizontal line represents the half-bandwidth

Results A 40^{th} order filter was able to provide a combined response very close to the desired one, with a half-maximum bandwidth at F=0.47 and a maximum ripple of 7.4% in the passband (fig. 2). Compared to the standard sliding window reconstruction, The velocity waveform after inverse filtering showed a restoration of the velocity dynamics with clear improvements of the rise time of the systolic peak and peak-to-peak amplitudes (fig 3).

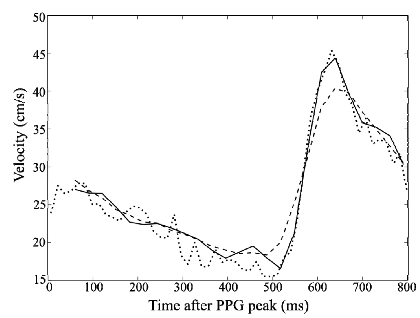

Fig. 3 Fully-sampled waveform (dotted), sliding window reconstruction (dashed), and inverse-filtered waveform (solid)

Discussion Sliding-window reconstruction is a useful tool for the reconstruction of phase-contrast data, increasing the temporal resolution of the acquired samples four-fold. However, this increase can result in distortion s of the dynamics of pulsatile blood flow velocities due to significant low-pass filtering effects. These can be compensated by appropriate inverse filtering, provided that a filter of sufficient order is used. A high-order filter can be applied by using the assumption of periodicity of the velocity signal, which is an inherent characteristic of cardiac-gated acquisitions. This reconstruction is able to effectively double the passband with respect to conventional phase contrast reconstruction with no penalty other than a small computational cost, therefore leading to a potential two-fold decrease of the total scan time.

References (1). Pelc NJ et al. J Magn Reson Imaging. 1991;1(4):405-13. (2) Santini F et al, Proc of ISMRM 2009, #4537 (3) Markl M, Hennig J. Magn Reson Imaging 2001;19(5):669-676.