Low latency vs. non linear phase: A balanced approach for UNFOLD filter design in quantitative Real-Time MRI

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Purpose/Introduction:

The UNFOLD method can be used to accelerate dynamic MRI acquisitions [1] and to remove artifacts in parallel-imaging and partial-fourier imaging [2]. The essential basic reconstruction step of the UNFOLD method is a temporal low-pass filter. Recent filtering approaches can be coarsely classified into spectral-domain filter methods such as finite impulse-response filter (FIR) and time-domain filtering methods such as infinite impulse-response filter (IIR) [3].

FIR filters have two important advantages over IIR filters. First, they are guaranteed to be stable and second, they may easily constraint to have a (generalized) linear phase. On the other hand, FIR filters have a symmetric impulse response and can thus in general not been designed to have the short latencies of IIRs which allow for asymmetric impulse responses [3]. In addition, compared to IIR filters, their implementation adds to the multiplication with the filter-coefficients two additional FFTs. Consequently, for MRI-applications requiring real-time reconstruction of MR data with low latencies (interventional imaging) and for the off-line reconstruction of extensive data-sets, IIR filters are in general preferable. However, their non-linear phase (vs. Frequency), or delay distortion, limits their use when a quantitative analysis of the temporal evolution of the MR-signal is needed (MR-guided thermotherapy, the quantification of contrast agent passages and fMRI).

Kellman's filter design [3] for interventional imaging, based on an elliptical-IIR, focused mainly on the aspect of low-latency of the filter. We propose an alternative design based on a Bessel-IIR, which maintains the low-latency aspect but reduces the phase-dispersion in the pass-band and is thus suitable for quantitative interventional applications such as MR-guided thermotherapy.

In addition, for the off-line reconstruction of UNFOLD encoded data-sets, we extend the proposed filter concept by cascading an additional matched all-pass filter which sacrifices latency but achieves a virtually linear phase response, which is is comparable to FIR filter designs, while maintaining the computational advantages of IIR filters. In order to demonstrate the different filter characteristics, we applied three IIR filter designs to a dynamic MRI data-set of a bolus passage through the kidney.

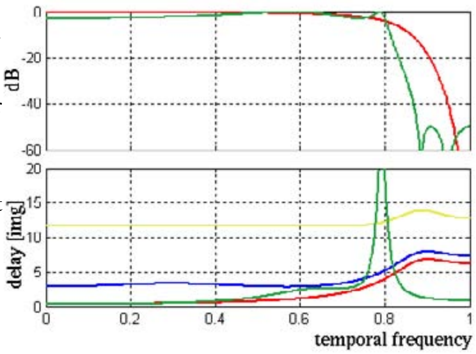

Figure 1: Filter characteristics (amplitude above, group delay below) of the elliptical IIR (green), the Bessel IIR (red), the Bessel IIR + 2nd order all-pass (blue) and 10th order all-pass (yellow).

Methods:

Filter: Four IIR-filter types were evaluated: An elliptical IIR low-pass filter (4th order) as proposed by Kellman et al., a Bessel IIR low-pass filter (4th order) and two additional IIR all-pass filters (2nd order and 10th order) which are matched to the Bessel IIR. The latter two can be cascaded with the Bessel IIR in order to equalize the group delay in the pass-band to three and twelve images, respectively, while maintaining the amplitude attenuation of the Bessel IIR. The IIR-filter coefficients were designed using the signal processing toolbox of MATLAB with the following characteristics: f_p=0.8, f_s=0.9, ripple pass-band: 3dB, ripple stop-band: 50dB as shown in figure 2. Subsequently, the filter coefficients were implemented into an in-house C++ MRI raw-data reconstruction toolkit.

MRI-data: Gadolinium bolus injection (normal dose) observed in the right kidney with a T_1-weighted gradient recalled echo with TE=1.1ms, TR=2.3ms , matrix=128x83, FOV=40x40cm^2, 400 images with 1.6s/dyn on a Philips Intera 1.5T. The patient was free-breathing during the data acquisition.

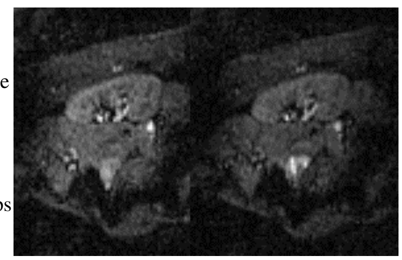

Figure 2: UNFOLD encoded image of a human kidney, reconstructed with the elliptical IIR (right) and the Bessel- IIR (left).

Results / Discussion:

Figure 2 shows one image out of the UNFOLD encoded data-set (two-fold acceleration) reconstructed with the Bessel-IIR and the elliptical-IIR. Despite the less-sharp transition between pass-band and stop band compared to the elliptical IIR, the Bessel IIR filter shows a similar level of artifact suppression.

Figure 3a shows the MRI-time course within an ROI in the cortex of the left kidney during a gadolinium bolus passage. The time-course is significantly altered after reconstruction with an elliptical IIR filter (3b) due to the suppression of high frequency components and due to the non-linear phase of the filter. The Bessel IIR filtered result conserves to a large extend the temporal characteristics of the signal (3c). Since for this type of application no real-time reconstruction is required, an additional cascaded matched all-pass IIR filter can be used to eliminate all nonlinear phase effects over the entire pass-band (3d). However, this increases the latency to 12 images for all temporal frequencies. This cascaded filter combination would in this example preserve the ability to quantify the signal evolution for perfusion/filtration measurements.

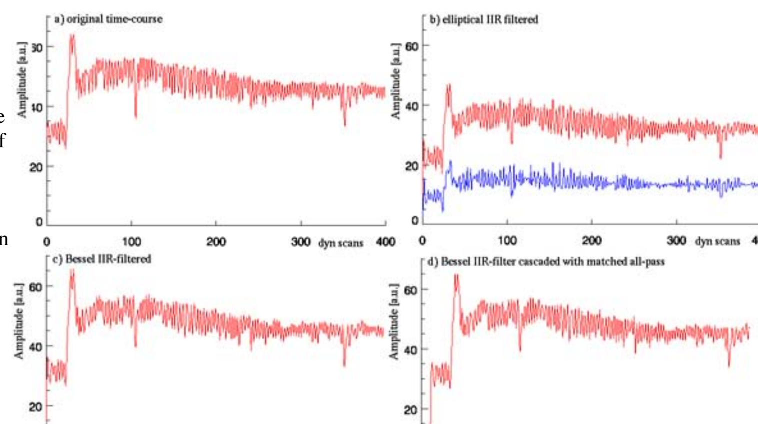

Figure 3: Time course of a bolus passage through the kidney (red) and the difference to the original data (blue).

Conclusion:

The proposed Bessel IIR filter is for UNFOLD encoded real-time MR-applications which require low latency in conjunction with a low phase-dispersion such as MR-guided thermotherapy an interesting alternative compared to previously published methods.

For UNFOLD encoded non real-time MR-applications which do not require low latency, such as bolus tracking or high temporal resolution fMRI-experiments, cascading IIR low-pass filters with a matched all-pass filter can eliminate the non-linear phase behavior of IIR filters while maintaining the substancial computational advantages of IIR methods compared to FIR methods.

References:

[1] Madore, B. et al., MRM 1999;42:812-828 [2] Madore, B. et al., MRM 2002;48:493-501 [3] Kellman, P. et al., MRM 2000;44:933-939