Simulation of Relative Temporal Resolution of Time-Resolved MRA Sequences

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Introduction

Time-resolved MRA sequences are characterized by the display frame rate and the duration of the temporal window used to gather all data required to reconstruct the displayed frame. For view-shared methods like keyhole [1] and TRICKS [2] the duration of the temporal window is often significantly longer than the displayed frame time, resulting in poor frequency response. We simulate here the temporal frequency response of three time-resolved MRA methods including a new sequence that exploits the recently introduced HYPR [3] reconstruction method implemented here with an angular under sampling factor of 20.

Theory and Methods

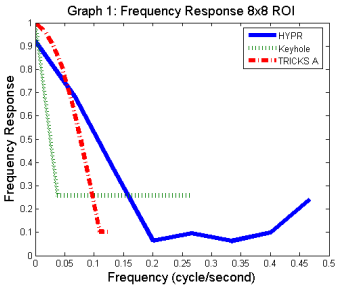
In conventional keyhole imaging, central k-space data is updated with a high frame rate while late, high spatial frequency data are pasted into all time frames providing no temporal frequency information. Therefore, the temporal reconstruction window is equal to the duration of the entire scan. In TRICKS, the center of k-space is sampled more frequently than other k-space segments. This results in a temporal resolution that varies with spatial frequency and the reconstruction window is typically 3-4 times longer than the displayed frame time. Under the condition that a sufficient number of angles are sampled in stack-of-stars HYPR imaging [4] the displayed frame time and the temporal duration of the reconstruction window are the same. If fewer than the optimal number of angles is used, there are not enough projections in a single time frame to suppress future or past signals imbedded in the composite causing the duration of the composite image to deteriorate the temporal response.

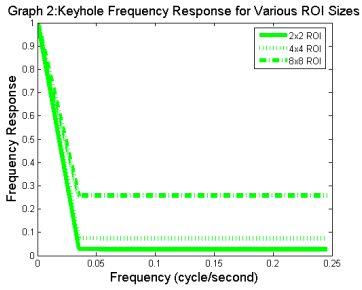
The temporal frequency response of these methods was simulated by placing a temporal impulse signal in the form of a delta function with an intensity of 200 units, the average vascular signal intensity within the vessels, into one basic reconstruction frame out of a 15 frame input data set. The input data for each simulation consisted of 512 x 512 DSA images interpolated into 15 DSA frames. The delta function for the TRICKS method was inserted into input frame nine, which was sampled for the A, or low spatial frequency region of k-space. This is the best case scenario; ghosting and a more dispersed impulse response function results from reconstructions when the delta function lies in frames sampled for the medium or high frequency regions of k-space, defined as B or C. To demonstrate the worst scenario, an impulse inserted into frame eight, which was sampled for the C region, was also simulated. For keyhole, the delta function was inserted into the eighth frame; to account for this, the high spatial frequency data pasted into all other time frames originated from the time frame that included the impulse, not from a late frame as conventional keyhole stipulates. In the HYPR simulation, the delta function was also inserted into one time frame, the eighth. The impulse response functions were adjusted to account for the time required to form the basic frames for each technique. The simulated keyhole reconstruction sampled the inner 15% of k-space at a high frame rate. TRICKS was simulated using nearest neighbor interpolation. Therefore, each reconstructed frame was 3-4 DSA frames wide.

The temporal Fourier transform of the impulse response function provides the shape of the temporal frequency response function for each method. For keyhole and TRICKS, the initial shape was sufficient and needed no normalization factor. HYPR was normalized at zero frequency using the response obtained when a DC signal was inserted instead of a delta function. Since the temporal frequency responses for some methods were dependent on spatial frequency, signal impulses of various spatial extents were used.

Results and Discussion

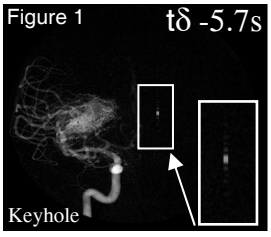
The impulse response functions show the spreading of the delta impulse through times other than those occupying the impulse. During the reconstruction of a 4x4 ROI, keyhole spreads 50% of impulse intensity throughout the entire duration of reconstruction, while accurately placing the 100% intensity at t. TRICKS and HYPR are more effective at correctly reconstructing a proper intensity of near zero for times with no delta function inserted, with HYPR dispersing the signal the least. A-region TRICKS spreads 89% of the signal to only one adjacent time frame; all other time frames have at most 1% of the signal reconstructed. C-region TRICKS displays a poorer impulse response function; only 13.5% of the signal is ever reconstructed and is also spread over 4 time frames.

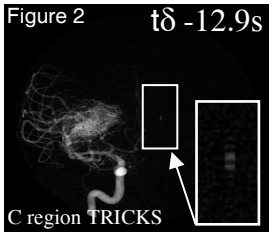


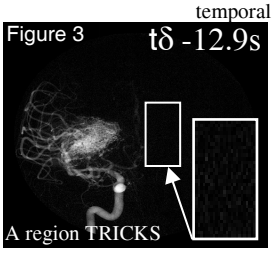


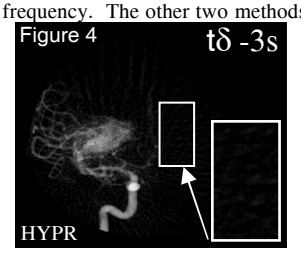
Graph 1 shows the differences in temporal frequency response between HYPR, keyhole and TRICKS for an 8x8 ROI. Keyhole shows only 25% response for frequencies over 0.037 cycle/second. TRICKS displays a response of at least 50% for all frequencies up to .077 cycle/sec, and continues to give response thereafter until .11 cycle/second. HYPR out performs both methods by giving responses exceedingly higher than the others for higher frequencies.

The frequency response functions for each method also vary with spatial frequency. As Graph 2 shows, keyhole exhibits a decrease in response of 23% between an 8x8 and a 2x2 ROI; for the higher spatial frequency, it gives a response of 2% for temporal frequencies over 0.035 cycles/second. Keyhole fails to reliably reconstruct high spatial frequency objects with high temporal frequency. The other two methods depend on spatial frequency as well but with much less consequence.









Figures 1-4 represent the result of each reconstruction method three frames prior to the insertion frame of the delta function. The impulse ROI that was inserted in the 8th time frame is already very distinguishable at a time t-5.7 seconds using the keyhole reconstruction method, correlating to its temporal reconstruction window being the entire length of acquisition. C-region TRICKS reconstructs 13.6% of the intensity at time t-12.9 seconds. A-region TRICKS does not reconstruct the impulse at t-12.9 seconds. Only at t-4.3 seconds does the impulse reconstruct. The impulse is not yet reconstructed in the 5th time frame of HYPR; time t-2 seconds is the first in which HYPR reconstructs the ROI at all, at 16%.

Conclusion The HYPR reconstruction method exhibits a far better temporal frequency response for a larger spectrum of temporal and spatial frequencies than the keyhole and TRICKS methods.

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References

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