Time-Resolved Imaging with Multiplicative Algebraic Reconstruction Technique (MART): An Application of HYPR Principles for Variable Density Cartesian Acquisitions

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Introduction: Multiplicative Algebraic Reconstruction Technique (MART) is an iterative method for reconstructing imaging data from a limited number of projection angles (1). In time-resolved MR imaging, only a limited number of projections or phase encodes can be acquired at the desired temporal resolution. As described in a separate submission, the time-resolved HYPR technique (2), as re-formulated by Huang and Wright (3), can be understood to be the first step of MART in which *a priori* information is provided through an initial estimate – the "composite" image reconstructed from data acquired over a period greater than the desired temporal resolution. Multiplication by a "weighting" image is a multiplicative update to the estimate, which, in the Huang-Wright implementation, is equivalent to a single iteration of the MART algorithm. While radial acquisitions have many advantages, Cartesian sampling is robust to gradient timing errors, is more amenable to tailoring the FOV in three dimensions, and better conditioned to parallel imaging. The purpose of this work was to integrate HYPR pre-conditioning into a MART algorithm designed for time-resolved reconstruction of 3DFT (Cartesian grid) data sampled in an interleaved variable-density pattern. As with I-HYPR (4), we iterate a number of times to refine the estimate and regularize by stopping iteration prior to convergence. Additional regularization proposed here is median filtering in the time dimension to suppress artifactual signal fluctuations.

Methods: A variable density 3DFT acquisition pattern was designed such that a cycle of N patterns interleave in k-space and time to produce an average k-t density proportional to $1/k_r$. Density was capped at 1 sample per time frame within a region near the center and normalized so as to drop to 1 sample every N time frames at the edge. Figure 1 shows one of N=16 sampling patterns for a 256×256 phase encode matrix. A numerical dynamic phantom was designed to simulate the arrival of contrast in several arteries of different sizes and arrival times as well as slowly enhancing background and complex Gaussian noise. Data acquisition was simulated by Fourier transforming the phantom at each time frame and sub-sampling the data with the sampling pattern for that time frame. Reconstruction of these simulated data was performed using a conventional nearest-temporal-neighbor technique as well as using the MART technique, which applies an iterative update of the form:

$$f^{(n+1)} = f^{(n)} \frac{H^t g}{H^t H f^{(n)}}$$

where f is the estimate (image), g is the k-space data acquired during the time frame, H is the imaging operator (k-space sampling at the set of points acquired during the time frame), and H^t, the adjoint of H, is the reconstruction operator (inverse discrete FT of the under-sampled data).

The regularized MART technique included: 1. averaging the data over the 16 timeframe window to form an initial estimate, 2. applying three iterations of multiplicative update using time frame data, and 3. applying a median filter in the time dimension as a final step.

Results: Figure 2 shows several time frames of the dynamic phantom and reconstructions of the phantom by means of the nearest-temporal-neighbor sliding window technique, and the proposed MART technique. Visual inspection indicates less reconstruction error is present in the MART images, as compared to the nearest-temporal-neighbor reconstructed images, both in terms of background artifact level and apparent temporal step-response. Figure 3 shows signal in the first small artery to enhance vs. time, demonstrating the step response function, and the derivative of this signal curve, demonstrating the shape of the "temporal footprint" associated with the combined acquisition and reconstruction.

Discussion: While the MART technique was developed for non time-resolved image reconstruction from projections, these results demonstrate that it can also be applied to time-resolved MR imaging where data are acquired with a variable k-t density 3DFT sampling pattern. Like the HYPR technique, a "composite" image, reconstructed from data acquired over several time frames, serves as an initial estimate, providing *a priori* information to condition the problem. The method could also potentially be applied where *a priori* information is provided by a separate acquisition, for instance a phase contrast image, analogous to the HYPR-flow technique (5). Limiting the number of multiplicative updates provides regularization. Information from neighboring time frames provides additional regularization in the form of median filtering in the time dimension, proposed here. While under-sampling introduces artifactual structure to the multiplicative update "weighting" image that may be imposed on the reconstructed image (particularly when sparcity is poor, e.g. presence of other vessels or enhancing tissue), each of the N sampling patterns produces a different artifact pattern, and thus may be largely removed by median filtering. This is also true for under-sampled radial acquisitions, and the method could potentially be applied to HYPR. In this example, the k-t density over the N sampling patterns met the Nyquist criterion, however the technique could provide further acceleration by reducing the sampling density and either accepting the well dispersed artifacts, or using parallel imaging to compute or correct for some or all of the missing data, e.g. (6).

References: (1) Gordon, J Theor Biol, 1970; 29:471-481. (2) Mistretta, MRM,2006; 55:30-40; (3) Huang, MRM, 2007; 58:316-325. (4) O'Halloran, MRM, 2008; 59:132-139. (5) Wu, ISMRM 2008 p 110. (6) Haider, ISMRM 2008, p 1271.

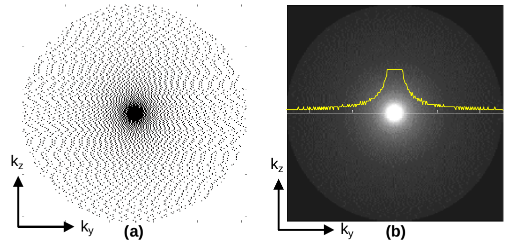

Figure 1: Cartesian acquisition with variable density interleaved sampling. (a) one of N=16 periodic sampling patterns. (b) k-t density over an interval of 16 time frames is proportional to capped $1/k_r$ (profile imposed on image).

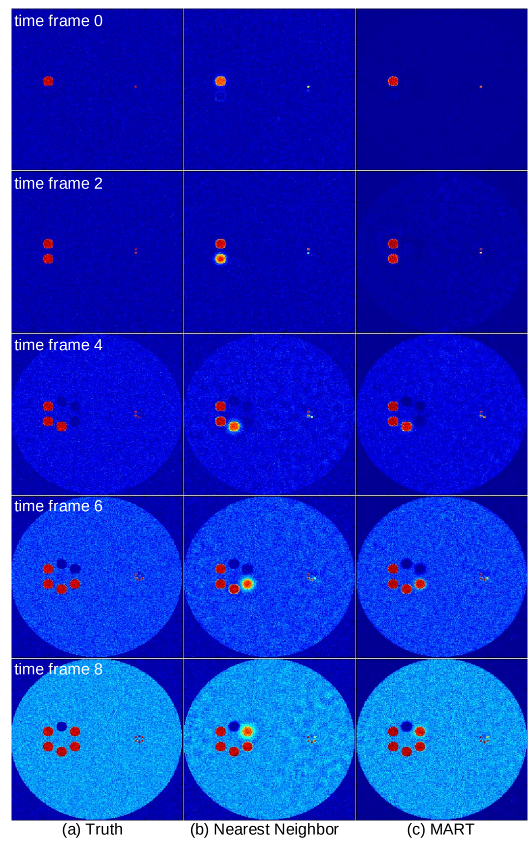

Figure 2: Simulation of arteries of various sizes with contrast arriving at various times. Several time frames (number w.r.t. initial arrival) are shown of (a) truth reference, (b) nearest temporal neighbor reconstruction, and (c) proposed MART reconstruction. The MART reconstruction exhibits fewer artifacts at the edges of vessels and dispersed throughout image (emphasized by blue-to-red color map), and enhancement dynamics more consistent with the truth reference.

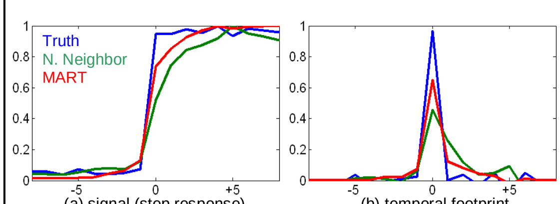

Figure 3: (a) Signal vs time frame in the first small artery to enhance demonstrates the step response function. (b) The derivative of the signal curve demonstrates the temporal footprint associated with the system (acquisition & reconstruction). MART is closer to the ideal step response.