Deterministic Comparisons of Nonlinear Acceleration Methods Using a Realistic Digital Phantom

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INTRODUCTION: In the last few years, several different accelerated imaging methods have been proposed that can speed the acquisition of dynamic processes. Clinical adoption of many of these methods has been slow, partially due to the difficulty in conclusively proving the method is providing additional, valuable information that would not otherwise have been available[1]. Many of these methods are nonlinear and based on sparsity, so it is crucial they be validated in realistic imaging environments. Inter- and intra-patient variability makes it difficult to obtain a valid gold standard dataset and it is often impractical or impossible to collect appropriate datasets to compare different methods. Here, we have compared two acceleration methods using a realistic digital breast phantom. To the best of our knowledge, this is the first comparison of Cartesian and non Cartesian methods with a known truth.

THEORY AND METHODS: We first implement a comparison in a simulated but realistic Dynamic Contrast Enhanced (DCE) Breast MRI data set. The digital phantom includes differentially enhancing background tissue and simulated, enhancing lesions. Improving the reconstruction of heterogeneously enhancing lesions could improve the specificity of DCE breast MRI. Heterogeneously enhancing lesions, which are frequently seen in breast MRI, present a challenge for current clinical reconstruction methods since an accurate reconstruction requires high spatial and temporal resolution.

Considerable effort was put into creating a gold standard to which Gaussian noise could be added. The digital phantom has the ability to provide multi-coil k-space data points appropriate for Cartesian and non Cartesian reconstruction methods. For this initial study, we chose to look at two acceleration methods, SPEAR[2], and Total Variation[3]. SPEAR is a Cartesian based reconstruction method that makes use of a variable density sampling pattern along the phase encode direction. The central lines of k-space are acquired for all time frames while higher spatial frequencies are acquired in an interleaved pattern as in k-t SENSE, then unaliasing is performed in the y-f domain[2]. We applied compressed sensing total variation minimization implemented through weighted least squares.

The phantom was used to generate k-space data points for these methods that all correspond to the same digital truth. In this initial study, we are interested at looking at the deterministic aspects of signal reconstruction so no noise has been added to the simulated k-space data. Each method was used to reconstruct 60 time frames during a simulated 10 and a half min DCE exam consisting of 100 slices. A reasonable TR achievable with fat suppression was determined for each method and an appropriate number of data points was provided to the method. Each algorithm generated reconstructed DCE images. From these results and the provided truth, normalized RMS error was be calculated in the spatial domain for specific slices and along the temporal dimension for specific lesion and normalized to the gold standard signal value for each voxel.

RESULTS AND DISCUSSION:

The results of the simulations can be seen in Fig. 1. Both of the methods have higher temporal RMS error in the initial part of the exam. This is likely due to the fact that the enhancement curves are changing very rapidly here. After this period, the methods perform well with average normalized RMS error values of 0.039 for Total Variation, and 0.006 for SPEAR for the locations displayed in Fig 1a.

In terms of spatial resolution, the Total Variation method suffers from blurring, most clearly depicted along edges. SPEAR maintains accuracy in the spatial domain with an average normalized RMS error of 0.0112 for the time frame shown in Fig 1.

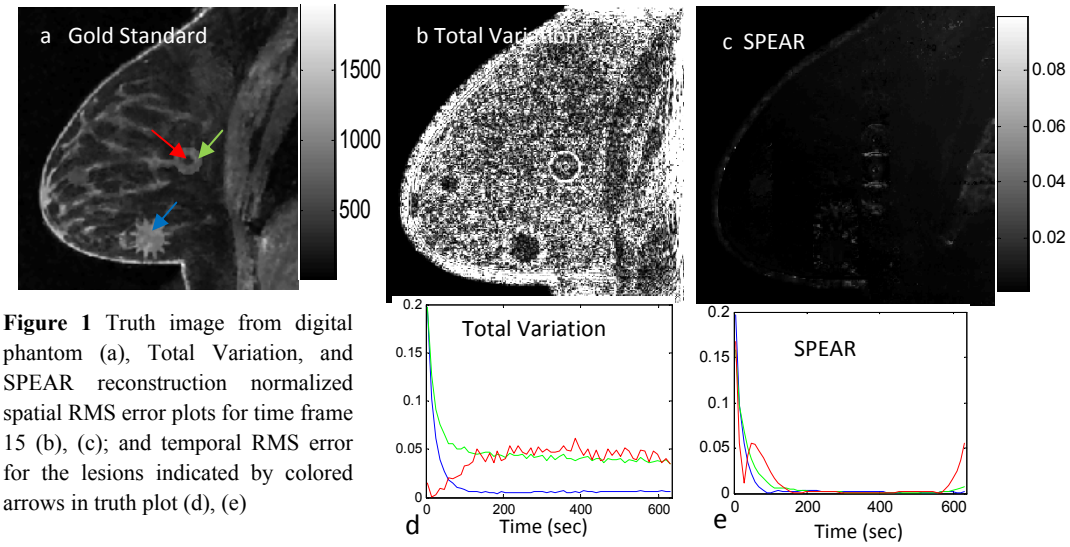

Figure 1 Truth image from digital phantom (a), Total Variation, and SPEAR reconstruction normalized spatial RMS error plots for time frame 15 (b), (c); and temporal RMS error for the lesions indicated by colored arrows in truth plot (d), (e)

This simulation highlights one of the strengths of SPEAR, the fact that it is exploiting data in both the spatial and temporal domain. This first assessment of deterministic performance performed with perfect sensitivity maps and no stochastic noise, allows for a strong performance of SPEAR in this simulation. The Total Variation method is only utilizing data from the spatial dimension so it is not able to perform as well. Adding a temporal constraint to the Compressed Sensing Total Variation Minimization algorithm would likely drastically improve its performance.

The next step in this analysis is to add noise to the simulated k-space data and to provide realistic sensitivity functions to see how robust the methods are in the face of noise and imprecision.

CONCLUSIONS: Here we have demonstrated the use of a digital phantom capable of creating simulated k-space data points for Cartesian and non Cartesian reconstruction methods. This phantom provides a known truth that all methods can be evaluated against, allowing for quantitative analysis of reconstruction performance. Though this phantom is designed specifically to study breast exams, the concept is applicable to any imaging situation[4].

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