2D graphical assessment for fast imaging strategies

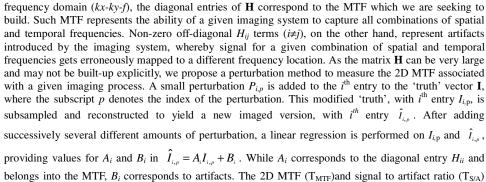**T-C. Chao[1,2], H-W. Chung[2], W. S. Hoge[1], J. Yuan[1], and B. Madore[1]**

[1]Department of Radiology, Brigham and Women's Hospital, Harvard Medical School, Boston, Massachusetts, United States, [2]Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan

Introduction: As the number and complexity of partially sampled dynamic imaging methods continues to increase, understanding how these methods relate and perform becomes increasingly difficult. Modulation transfer functions (MTF) have been used extensively in medical imaging in general, and X-ray imaging in particular, to evaluate the performance of imaging systems. An MTF graphically displays the ability of a given imaging system to correctly capture a range of spatial frequencies. In dynamic imaging, 2D MTF can be used to capture temporal frequencies in addition to spatial frequencies. Noise and artifact measurements are also proposed. Three fast imaging strategies, kt-SENSE[1], UNFOLD-SENSE[2] and a hybrid combination of the two, hybrid SENSE[3], are tested using the graphical approach described here.

Systole Diastole

Fig 1

Theory: Consider an imaging process described as $\mathbf{K} = \mathbf{EI} + \boldsymbol{\eta}$, where $\mathbf{K}$ is the signal from an object $\mathbf{I}$ (in either x-y-z-t, k_x-k_y-k_z-f or an hybrid space), encoded by $\mathbf{E}$ and with noise $\boldsymbol{\eta}$. The corresponding least-square reconstruction can generally be expressed as

$$\hat{\mathbf{I}} = (\mathbf{E}^H \mathbf{FE} + \lambda \mathbf{L}^H \mathbf{L})^{-1} \mathbf{E}^H \mathbf{FK} = \mathbf{HI} + \hat{\boldsymbol{\eta}}, \text{ where } \hat{\mathbf{I}} \text{ represents the reconstructed signal with noise } \hat{\boldsymbol{\eta}}, \mathbf{F} \text{ is an optional filter}$$

and $\mathbf{L}^H \mathbf{L}$ is the regularization term with weight λ. The $\mathbf{H}$ matrix essentially transfers signal from the actual object to its imaged version, and would be an identity matrix for an ideal imaging system. In a case where $\m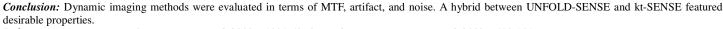athbf{I}$ is expressed in the spatial-temporal frequency domain (kx-ky-f), the diagonal entries of $\mathbf{H}$ correspond to the MTF which we are seeking to build. Such MTF represents the ability of a given imaging system to capture all combinations of spatial and temporal frequencies. Non-zero off-diagonal H_{ij} terms ($i{\neq}j$), on the other hand, represent artifacts introduced by the imaging system, whereby signal for a given combination of spatial and temporal frequencies gets erroneously mapped to a different frequency location. As the matrix $\mathbf{H}$ can be very large and may not be built-up explicitly, we propose a perturbation method to measure the 2D MTF associated with a given imaging process. A small perturbation $P_{i,p}$ is added to the ith entry to the 'truth' vector $\mathbf{I}$, where the subscript p denotes the index of the perturbation. This modified 'truth', with i^{th} entry $I_{i,p}$, is subsampled and reconstructed to yield a new imaged version, with i^{th} entry $\hat{I}_{i,p}$. After adding successively several different amounts of perturbation, a linear regression is performed on $I_{i,p}$ and $\hat{I}_{i,p}$, providing values for A_i and B_i in $\hat{I}_{i,p} = A_i I_{i,p} + B_i$. While A_i corresponds to the diagonal entry H_{ii} and belongs into the MTF, B_i corresponds to artifacts. The 2D MTF (T_{MTF}) and signal to artifact ratio ($T_{S/A}$) are defined by $\mathbf{T_{MTF}}(ky,f) = \sqrt{\sum_x |\mathbf{A}(x,ky,f)|^2 / N_x}$ and $\mathbf{T_{S/A}}(ky,f) = \mathbf{T_{MTF}}(ky,f)\sqrt{\dfrac{\sum_x |\mathbf{I}(x,ky,f)|^2}{\sum_x |\mathbf{B}(x,ky,f)|^2}}$.

Methods: Three fully sampled cardiac cine datasets were subsampled by factors of $R=4$ and $R=8$, and reconstructed with three different fast imaging approaches featuring different sampling and regularization schemes: kt-SENSE, UNFOLD-SENSE, and a hybrid of the two whereby UNFOLD-SENSE is merged with the regularization scheme from kt-SENSE[1]. Two frames from one of these datasets, acquired on a 3T scanner, are shown in Fig.1. UNFOLD-SENSE utilized a Tikhonov regularization of the form $(\mathbf{S}^H \boldsymbol{\Psi}^{-1} \mathbf{S} + \lambda)^{-1} \mathbf{S}^H \boldsymbol{\Psi}^{-1}$, and the other two used the kt-SENSE scheme featuring an $\mathbf{M}$ matrix with prior knowledge $(\mathbf{S}^H \boldsymbol{\Psi}^{-1} \mathbf{S} + \lambda \mathbf{M}^{-2})^{-1} \mathbf{S}^H \boldsymbol{\Psi}^{-1}$. The T_{MTF} and $T_{S/A}$ were computed for each method and each acceleration setting (Fig. 2). Furthermore, noise amplification was also measured, through a Monte Carlo approach. Iterations $r = 1$ through 45 were performed with different additive noise maps, and the amplification was defined as $\mathbf{R}(ky,f) = \sqrt{\dfrac{\sum_x Var\{\hat{\mathbf{I}}_r(x,ky,f)\}}{\sum_x Var\{\mathbf{I}_r(x,ky,f)\}}}$.

Fig 2

UNFOLD-SENSE   kt-SENSE   Hybrid-SENSE

R=4

k_y

R=8

f

(a) MTF

R=4

R=8

(b) Noise amplification

R=4

R=8

(c) Signal to artifact ratio

Results and Discussion: Fig 2 graphically shows the results for one of the cardiac datasets. In the MTF image of Fig 2a, dark bands illustrate the signals in k_y-f space that are suppressed in the reconstruction. The two methods using kt-SENSE's $\mathbf{M}$ matrix for regularization better maintain their performance as the acceleration factor is increased (see Figs. 2a and 2c, for kt-SENSE and hybrid-SENSE). The methods using UNFOLD-SENSE's sampling strategy captured a continuous temporal frequency region, without black vertical lines at given temporal frequency locations (see Figs. 2a and 2b, for UNFOLD-SENSE and hybrid-SENSE). kt-SENSE had a higher signal-to-artifact ratio at temporal DC (Fig. 2c). Overall, at least over the acceleration range tested, hybrid-SENSE seemed to combine strengths from the two other approaches, as it maintained reasonably good performance at higher acceleration (like kt-SENSE) and captured an uninterrupted range of temporal frequencies (like UNFOLD-SENSE). While Fig. 2 was obtained from the dataset in Fig. 1, similar MTF, artifact, and noise results were obtained using the other two datasets.

Conclusion: Dynamic imaging methods were evaluated in terms of MTF, artifact, and noise. A hybrid between UNFOLD-SENSE and kt-SENSE featured desirable properties.

References: [1].Tsao, J., et al.,Magn Reson Med, 2003.p.1031-42 [2].Madore, B.,Magn Reson Med, 2002.p.493-501
[3].Madore, B. in ISMRM. 2008.p.1496