Neonatal MRI Acceleration Using Correlation Introduced by Across-Slice Data Sparsity

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Introduction: Data sparsity has been used in compressed sensing to accelerate MRI. In image space, MRI data sparsity manifests as neighboring data correlation. This image-space data correlation cannot be effectively used to estimate missing data in high-speed MRI because the data acquisition and undersampling are performed in k-space. The presented work proposes a "virtual" image-space data acquisition scheme in multi-slice 2D imaging, allowing for MRI acceleration by directly utilizing image-space correlation introduced by k-space data sparsity. The proposed approach is developed for clinical MRI of neonates on a 1.5T small bore (21.8 cm) scanner within the Neonatal Intensive Care Unit (NICU). Ideally, the neonates are not sedated for the MRI exam making short acquisition times essential to obtaining good diagnostic image quality. However, parallel imaging acceleration on the NICU scanner is limited by the restricted spatial encoding capability of the small coil arrays sized to match the neonatal anatomy. To overcome this challenge, a framework of "correlation-based reconstruction" [1] is used to convert high-speed imaging reconstruction to the estimation of correlation functions. Here we developed an image-space model that can estimate the missing data in image-space acquisition using neighboring data correlation introduced by k-space data sparsity. By so doing, we provide an approach to accelerating neonatal MRI with or without parallel imaging. In the presented work, we demonstrate this new approach in an extreme case: Neonatal MRI performed with a single-channel volume birdcage coil that is incapable of parallel imaging.

Theory: As shown in Figure 1(a), data acquisition and reconstruction for neonatal MRI are modeled in image space. This is not correct if considering the actual procedure of data acquisition. As shown in Figure 1(b), however, multi-slice 2D imaging data can be considered as image-space acquisition in the slice direction for every k-space phase encoding line. By 1D inverse Fourier transform in the fully-sampled frequency encoding direction, a 2D data acquisition domain can be "virtually" generated along the frequency-encoding and the slice directions in image space. A linear filter $u(x, y)$ in this "virtual" data acquisition domain is used for image reconstruction, i.e., the neighboring data correlation across slices is used to estimate missing k-space phase-encoding lines in image space. This data correlation exists because the "virtually" acquired 2D image-space data are sparse in Fourier transform domain (k-space). In the presented work, this model is used for single-channel imaging that cannot be accelerated by parallel imaging. The least square solution to the linear filter $u(x, y)$ for reconstruction in Figure 1 can be resolved from a set of linear equations given by [1, 2]:

$$\sum_{x',y'} c_d(x'-x,y'-y)t_s(x'-x,y'-y)u_i(x',y')=c_d(-x,-y),\quad (x,y)\in\{(x,y)\,|\,u(x,y)\neq 0\}$$

where $c_d(x, y)=sum\{[d(x', y')]\cdot conjugate[d(x'+x, y'+y)]\}_{\text{over } x', y'}$ represents the image-space correlation functions, and $t_s(x, y)$ is a previously determined undersampling trajectory. This equation is in the same format as that demonstrated in our previously proposed "correlation-based reconstruction" framework [1]. However, in this implementation, a different definition of correlation is used to quantify image-space correlation introduced by k-space data sparsity across slices. This image-space correlation can be estimated from the reference images provided by auto-calibration signals (ACS), as indicated in Figure 1(b).

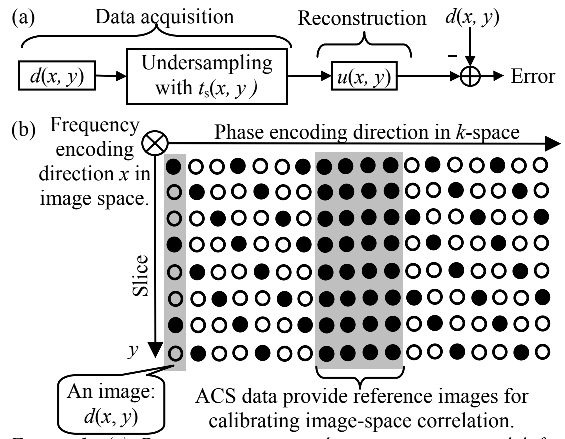

Figure 1. (a) Data acquisition and reconstruction model for single-channel neonatal MRI. $t_s(x, y)$: undersampling trajectory in image space; $u(x, y)$: linear filter for reconstruction in image space. (b) High-speed multi-slice 2D imaging can be considered as image-space undersampling along the slice direction. Solid dots represent sampled lines and empty dots are missing data.

Methods and Materials: A 3.2 kg neonatal sheep at 85% full gestational age was imaged four hours after birth on a 1.5T 21.8 centimeter bore scanner using a 14.5 centimeter birdcage coil. The size, shape and weight of the premature sheep are similar to that of a premature human neonate. A set of spine images was acquired using a multi-slice 2D turbo spin echo sequence (FOV 145×145 mm, matrix 256×256, TR/TE 4000/100 ms, TSE factor 12, flip angle 12°, 30 slices with 4 mm thickness and 1 mm gap). The phase encoding direction was left-right. The fully-sampled data were uniformly undersampled in post-processing. A total of 48 ACS lines (48 reference images in "virtual" data acquisition domain) were used. The correlation functions estimated from each reference image are summed together as the final estimate for the reconstruction of missing k-space phase encoding lines in each "virtual" image in the frequency-encoding and the slice directions.

Results and Discussion: Figure 2(a) shows an image acquired in the "virtual" data acquisition domain for a center k-space phase encoding line (k=0). It can be seen that this image has k-space sparsity and image-space correlation. By integrating this correlation into correlation-based reconstruction, image information can be preserved with a net acceleration factor of 2.56 (R=4, ACS=48), demonstrating the image-space correlation introduced by k-space data sparsity can be used to accelerate MRI data acquisition. It should be noted that compressed sensing is an alternative approach to image reconstruction in this work. For use in neonatal MRI, however, random sampling capability is limited due to the complexities of clinical pulse sequence development and the difficulty in suppressing unpredictable gradient noise which is of particular concern in the NICU environment. Correlation-based reconstruction uses uniform undersampling, providing sufficient simplicity for clinical translation. Since this approach is compatible with parallel imaging, we are working on how to synergistically integrate this work into a conventional parallel imaging framework by defining a generic correlation function that includes both coil sensitivity and data sparsity information for further MRI acceleration.

Reference: [1]. Li, Y. et al. ISMRM 2011; 19: 745. [2]. Hayes M. New York: John Wiley & Sons, Inc; 1996.

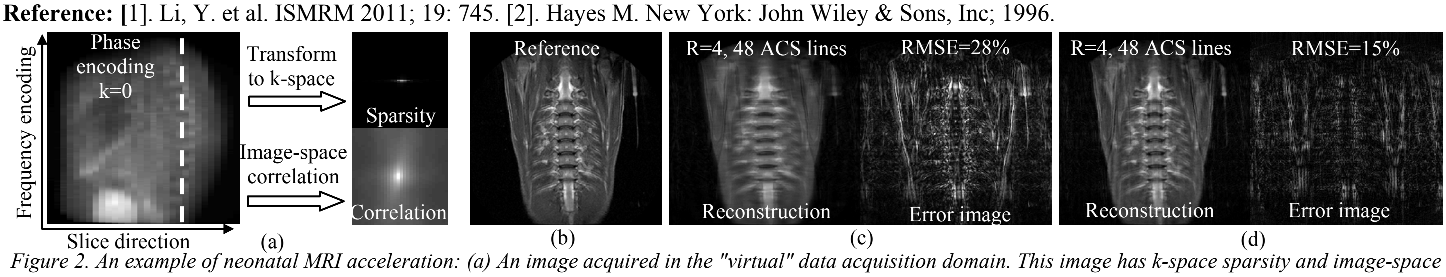

Figure 2. An example of neonatal MRI acceleration: (a) An image acquired in the "virtual" data acquisition domain. This image has k-space sparsity and image-space data correlation. (b)A reference image (fully sampled) at the location of dashed line in (a). (c) Direct Fourier reconstruction from undersampled data with a reduction factor of 4 and 48 ACS lines. (d) Reconstructed results using correlation-based reconstruction in image space. The improvement in resolution can be observed by comparing (c) and (d). The gain in Root-Mean-Squared error (RMSE) quantifies the image information provided by image-space correlation in reconstruction.