Parallel imaging using a non-uniform undersampling trajectory

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Introduction: The work presented here introduces a novel parallel imaging technique that uses a non-uniform k-space undersampling trajectory to accelerate Cartesian data acquisition for MRI. In this technique, a non-uniform undersampling trajectory is formed from multiple uniform sub-trajectories with higher undersampling factors. Based on a modulation model for uniform undersampling, we separate non-uniformly undersampled data into real and aliasing image data in k-space. This provides an approach to reconstruction by designing linear k-space filters that pass real image and block aliasing, with the computation cost comparable to that using a uniform trajectory. In a high-resolution brain imaging experiment, we compared this new technique with a standard GRAPPA technique [1] that uses a uniform undersampling trajectory. It was demonstrated that parallel imaging with a non-uniform trajectory can provide better imaging quality than that with a uniform one when a high acceleration factor (>4) is used with a conventional 8-channel head coil array.

Theory: In the modulation model [2] given by Fig. 1, a set of data uniformly undersampled by a factor of R can be mathematically represented as the sum of R sets of fully sampled data modulated with different harmonics. It should be noted that the data modulated with zero frequency harmonic (n=0) are the original fully sampled data (real image data), and the other data modulated with non-zero frequency harmonics are the aliasing image data. This modulation model provides a way to separate uniformly undersampled data into real and aliasing image data in k-space. Based on this modulation model, we can develop an approach to reconstruction from data acquired using a non-uniform undersampling trajectory that can be formed from multiple uniform sub-trajectories with higher undersampling factors. As an example, Fig. 2 shows how a non-uniform trajectory with the net undersampling factor of 2 is equivalently formed from two uniform sub-trajectories with the undersampling factor of 4. By combining the modulation model representations of two uniform sub-trajectories, one can find that two aliasing replicas for the non-uniform trajectory in Fig. 2 are:

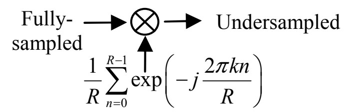

Fig. 1 *A k-space modulation model for uniform undersampling. R, undersampling factor; k, phase encoding line indexes.*

$$\text{Aliasing \#1} = \frac{1+j}{4}\text{Image}\left(\text{shifted by}\frac{\text{FOV}}{4}\right) \text{ and Aliasing \#2}=\frac{1-j}{4}\text{Image}\left(\text{shifted by}\frac{3\text{FOV}}{4}\right).$$

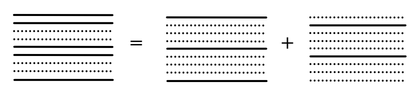

Fig. 2 *A non-uniform undersampling trajectory is equivalent to two uniform sub-trajectories. The solid lines indicate the undersampling trajectories.*

where FOV is the field of view in phase encoding direction. By directly using the modulation model, one can find that a uniform trajectory with the undersampling factor of 2 generates only one aliasing replica:

$$\text{Aliasing \#1} = \frac{1}{2}\text{Image}\left(\text{shifted by}\frac{\text{FOV}}{2}\right).$$

Therefore, compared with uniform undersampling, non-uniform undersampling generates more aliasing replicas that have lower magnitude and appear at different locations. It should be noted that the non-uniform trajectory used in this work will not introduce considerably high computation cost in reconstruction: The use of modulation model in Fig. 1 separates the aliasing data from the real image data in k-space and low-resolution calibration data can be used to calculate a set of linear filters that pass the real image data and block the aliasing data. By applying linear filters to the non-uniformly undersampled data, reconstruction can be implemented in the same way as that using a uniform trajectory. The critical issue of the presented work is: which trajectory, uniform or non-uniform, is more favorable to aliasing suppression in reconstruction?

Methods and Materials: We experimentally investigated the critical issue of this work in brain imaging using a conventional 8-channel head coil array (Invivo, Gainesville, FL) on a 3T MRI scanner. A set of axial images were acquired with full Fourier encoding using a T_1 FLAIR sequence (FOV 220×220 mm, matrix 512×512, TR/TE 3060/126 ms, flip angle 90°, slice thickness 5 mm, number of averages 1). The phase encoding direction was left-right. Parallel imaging data with acceleration were generated by undersampling during post processing. The same data reduction factors were used in non-uniform and uniform undersampling. A standard GRAPPA technique was used for reconstruction from uniformly undersampled data as a reference. The calibration data were 24 center k-space lines. Using the same calibration data, we calculated a set of linear filters (finite length 2×2) to reconstruct images from non-uniformly undersampled data and compared with GRAPPA.

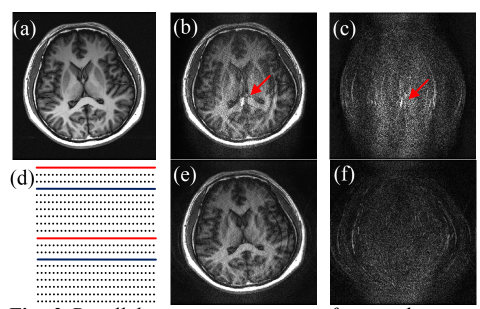

Fig. 3 *Parallel imaging using a uniform and a non-uniform trajectory with an acceleration factor=5. (a) Reference image from fully sampled data. (b) GRAPPA with a uniform trajectory. (c) Difference image between (a) and (b). (d) A non-uniform undersampling trajectory formed from two uniform sub-trajectories with an acceleration factor of 10. The solid lines of two different colors (red and blue) indicate the two sub-trajectories. (e) Reconstructed image using the non-uniform trajectory in (d). (f) Difference image between (a) and (e).*

Results and Discussion: It should be known that the coil array used in this work has at most 4 elements in any physical direction implying a conventional parallel imaging technique may perform well only if the acceleration factor ≤4. In our experiments, it was found that the parallel imaging acceleration using GRAPPA with a uniform trajectory is limited by this number. However, the use of a non-uniform undersampling trajectory can reduce this limitation. Fig. 3 shows an example with an acceleration factor of 5. In Figs. 3(b) and (c), it can be seen that GRAPPA images have destructive aliasing artifacts in the center region of brain (marked by red arrows). Fig. 3(d) shows the non-uniform trajectory used in this example. This trajectory is formed from two uniform sub-trajectories (solid lines with two different colors) with an acceleration factor of 10. From Fig. 3(e), it can be seen that the destructive aliasing artifacts in GRAPPA are effectively removed in reconstruction indicating non-uniform sampling is advantageous over uniform sampling in parallel imaging if a high acceleration factor is used. This gain arises from the shift of aliasing replicas from center to the peripheral regions of the brain image and the reduction of aliasing image magnitude. It should be understood that we have multiple options to form a non-uniform trajectory from 2 or more than 2 uniform sub-trajectories for a given acceleration factor. The search for the optimal trajectory from a number of choices is challenging. An effort focused on how to optimize a non-uniform undersampling trajectory for further improved parallel imaging performance at high acceleration factors is underway in our research group.

Reference: [1]. Griswold, M. A. et. al., MRM 2002, 47:1202-1210. [2]. Li Y. et al., Proc. of ISMRM 2010; 18: 553.