Random phase modulation of spatial aliasing in temporal domain for dynamic MRI

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Introduction: Parallel imaging has been widely used in dynamic MRI for improved spatial or temporal resolution. In this study, we propose a new k-t space sampling trajectory for dynamic parallel imaging techniques. This method applies a random phase modulation to the spatial aliasing of images in temporal domain. As a result, the spatial aliasing induced by k-space undersampling at every time frame has a noise pattern in temporal dimension. By applying a temporal constraint that can be known from the priori knowledge of dynamic MRI data, the noise-like aliasing can be easily removed. This work uses the fMRI and cardiac imaging applications as examples to demonstrate the feasibility of the proposed method.

Theory: Consider undersampling a set of 2D k-space data with a reduction factor of *R*. One will have *R* choices of undersampling trajectories, which correspond to the use of different k-space shifts, $m=0,1,2,\ldots,R-1$, in phase encoding direction. The aliased image $A_m(r)$, corresponding to the sampling trajectory with a k-space shift equal to *m*, can be given by the below equation:

$$A_m(r) = I(r) + \sum_{n=1}^{R-1} I\left(r - n\frac{FOV_{ph}}{R}\right)\exp\left(-j\frac{2mn\pi}{R}\right) \qquad (1),$$

where *r* represents the spatial position in phase encoding direction in image space, FOV_{ph} is the field of view in phase encoding direction, and $I(r)$ represents the real image. In this equation, the first term $I(r)$ is the real image value at the spatial position *r* and the other terms are the image aliasing from other positions. It should be noted that the aliasing has a phase term $-(2mn\pi)/R$ dependent on the relative k-space shift *m*. It is accordingly possible to apply a phase modulation to the aliasing in temporal domain by changing the relative shift *m* with time in dynamic imaging. If we can make this k-space shift randomly changed, the spatial aliasing signal will have a noise pattern in temporal domain.

Methods and Materials: An example of data acquisition scheme with a reduction factor equal to 4 is shown in Fig. 1. In this scheme, every 4 sequential time frames form a basic cycle. In every cycle, each of the 4 different trajectories (corresponding to $m=0,1,2,3$) is used once at one of the 4 time frames. The order of these four different trajectories is randomly changed from one cycle to another. The corresponding relative k-space shifts (*m*) form a random time sequence. This will give a random phase modulation of spatial aliasing in temporal domain based on equation (1). The temporal summation of those data acquired from multiple cycles gives two components: 1) A set of fully sampled data of static images, and 2) the temporal summation of spatial aliasing of dynamic images. The second component will be small because the spatial aliasing of dynamic images has temporal phase incoherence due to random phase modulation. Therefore, the temporal summation is a very good approximate to the static images, which can be used as the training data for the calibration of reconstruction. In a particular dynamic MRI application, the signal usually has a certain temporal correlation. For example, the fMRI signal is correlated to the temporal behavior of external stimuli and the cardiac imaging signal is correlated to the motion of heart. Based on the priori knowledge about this temporal behavior, a temporal constraint can be applied to the data in temporal dimension. Because the spatial aliasing of images has a noise pattern in temporal dimension with the application of random phase modulation, the use of temporal constraint will efficiently remove the aliasing due to incoherency. In this work, the proposed technique was tested in two applications: fMRI and cardiac imaging. A fMRI experiment was performed using checkerboard visual stimulation with a 16s on/off block design. In a 4 minutes run, a healthy volunteer was scanned using a single shot gradient echo EPI on a SIEMENS Trio 3T scanner with an 8 channel coil array (128 volume images, TR 2000ms, TE 30ms, Flip angle 70°, FOV 220mm, Matrix 64×64, Slice thickness 3.3mm, Slice gap 4mm, Number of slices 33). In the cardiac imaging experiment, a set of cardiac function data were acquired using cine true FISP sequence on a 3T SIEMENS scanner with a 32 channel coil array (FOV 340×255 mm, matrix 384×150, heartbeats per acquisition 10, phase encodes per segment 7, number of phases 29, TR 2.86 ms, TE 1.43 ms, flip angle 46°, slice thickness 6 mm, number of averages 1). The fully sampled fMRI and cardiac data were manually undersampled by a factor of 4 at each time frame. The proposed k-t space sampling trajectory was used in undersampling for random phase modulation of spatial aliasing along time frames. A SENSE technique was used for reconstruction [1]. The results were evaluated in reference to k-t GRAPPA with a regular time-interleaved sampling trajectory [2].

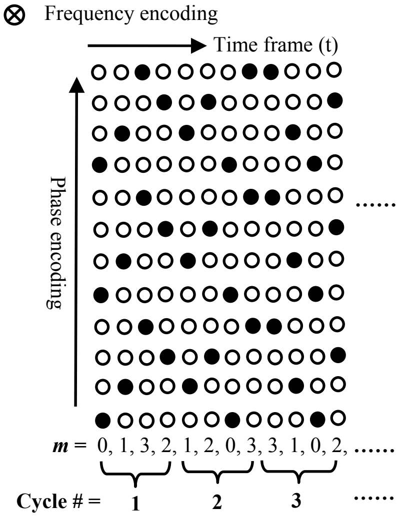

Fig. 1 A data acquisition scheme of random phase modulation in temporal domain with a reduction factor of 4.

Results and Discussion: Fig. 2 shows an example of the statistical analysis on correlation of the fMRI time series and the external stimuli. Compared with the reference correlation map in Fig. 2(a), the correlation map generated from the undersampled data using the time-interleaved trajectory has substantial errors, as shown in Fig. 2(b). The use of random phase modulation in temporal domain in undersampling can efficiently improve the analysis results: The generated correlation map in Fig. 2(c) is very close to the reference map in Fig. 2(a) except that the correlation coefficients are slightly lower because of extra noise induced by spatial aliasing. Fig. 3 shows an example of cardiac imaging reconstruction. It can be seen that the reconstruction error using the proposed method is close to that using k-t GRPPA. However, the proposed method shows slightly higher resolution in the regions marked with arrows. Further work will focus on the use of advanced regularization techniques to further improve the performance.

Reference: [1]. Prussmann , K.P. et. al., MRM 1999, 42: 952-962. [2]. Huang F. et al., MRM 2005; 54: 1172-1184.

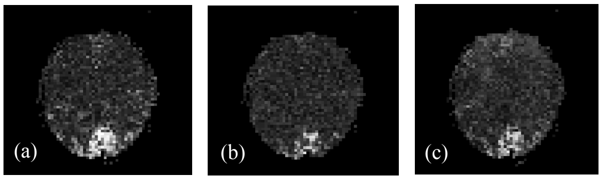

Fig. 2 An example of fMRI data analysis. The regions of high correlation are the activation regions in vision cortex. (a) A reference correlation map calculated from the fully sampled data. (b) A correlation map calculated from regularly undersampled data (time-interleaved). (c) A correlation map calculated from the undersampled data with the use of random phase modulation of spatial aliasing in temporal domain. The reduction factor in (b) and (c) is 4.

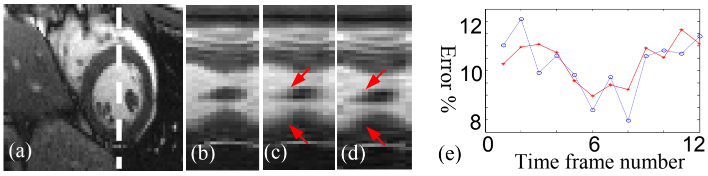

Fig. 3 An example of cardiac imaging reconstruction. (a) Reference image at the first time frame. (b), (c) and (d) show the time trajectories of image signal along the vertical line in (a). The time frame change is in horizontal direction. (b) Reference image signal. (c) Reconstructed image signal using k-t GRAPPA. (d) Reconstructed image signal using the proposed method. (e) Reconstruction error of the presented image region in percent with respect to reference image against time frame. The blue dashed line is for k-t GRAPPA. The red solid line is for the proposed method.