Efficient Hybrid Parallel Imaging Reconstruction with Rotating Radiofrequency Coil Array

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Introduction: The rotating radiofrequency coil (RRFC) is a novel MR imaging modality, wherein a RF coil moves about the subject to transmit RF wave and receive MR signals [1-2]. Recent studies have demonstrated that, by increasing the velocity of rotation and the signal sampling rate, the RRFC approach can theoretically accelerate the image acquisition with large reduction factors (R), whilst it only demonstrated R=2 in experiment. In order to further reduce the scan time in a practical manner, the RRFC concept has been combined with a 4-element coil array configuration to form the rotating radiofrequency coil array (RRFCA) [3] with a constant angular velocity. By strategically choosing the rotating velocity and imaging parameters (e.g, TR and TE), good performance with large acceleration has been demonstrated [3]. The system matrix of RRFCA is however more complex than that of stationary array, which leads to longer reconstruction times. Here we propose an alternative approach of imaging acceleration with RRFCA. In this new approach, the RRFCA revolves around the subject in a stepping fashion instead of having a constant angular velocity. RRFCA acquires a new position (typically a few degrees away) between two adjacent acquisition times (T_{ACQ}) and stays stationary within each T_{ACQ}. Please refer to abstract "Highly Accelerated Parallel Imaging using Rotating Radiofrequency Coil Array at 7T" (3916) for more details. Similar to the fast-mode [1-3], a large number of sensitivity profiles can be employed for image encoding compared with conventional stationary phased-array coils (PACs). However, the stepping-mode is advantageous in that it is easier to control and the image reconstruction is more efficient without the complication of time-varying sensitivity. In this paper, a fast hybrid image reconstruction strategy is described to further improve the efficiency and accuracy of accelerated image reconstruction with RRFCA.

Method: It has been demonstrated that parallel image reconstruction can be achieved with an iterative approach [4], which is suitable for solving simultaneous linear equations with a large number of unknowns. However, it is also known that a good initial estimate of the solution is critical to the solution time and quality. Due to the rotating movement, k-space data are encoded with different sensitivities, and hence the fast initial estimate cannot be realised by zero-padding inverse Fourier transform (IFT) [5]. The aim of this work is to provide fast and accurate initial estimate in a feasible way for the iterative reconstruction framework of RRFCA.

$$m = W \times \rho \quad (1)$$

$$W(k,r) = F(k,r).*S(r) = e^{-2\pi jk\cdot r}.*S(r) \quad (2)$$

$$m = F \times (\rho .* S) \quad (3)$$

$$\rho = (F^{-1} \times m)./S = R \times m \quad (4)$$

$$R(r,k) = e^{i2\pi r\cdot k}./S(r) \quad (5)$$

$$R_n(r,k) = e^{i2\pi r\cdot k}./S_n(r,t) \quad (6)$$

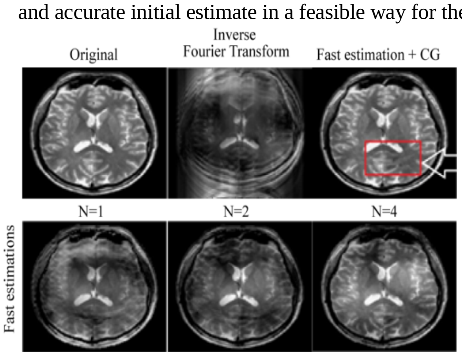

Fig.1 The image reconstruction simulation with fast estimation method.

The forward MR signal encoding process with a RF receiver is shown in Eq. (1), where m is the k-space samples and ρ is the proton density to be solved. As shown in Eq. (2), *W* is the combined Fourier (*F*) and sensitivity (*S*) encoding matrix; *k* (*k* = 1, 2, …, *K*) and *r* (*r* = 1, 2, … *R*) are indices of the *k*-space samples (*m*) and the spatial domain proton density distribution (*ρ*), respectively. Since the sensitivity encoding is identical for each line of *W* matrix (in Eq. (2), *S* has no *k* index), the identical S can be extracted from *W* and dot multiplied to *ρ* vector, as shown in Eq. (3). A simple derivation arrives at Eq. (4), with the element of matrix *R* described in Eq. (5). In essence, Eq. (4) represents an efficient means of recovering image from *k*-space samples. The reconstruction matrix *R* consists of inverse Fourier matrix (F^{-1}), which is readily calculated, followed by the dot-dividing the columns of coil sensitivity. This method has the potential to introduce singularities in the matrix *R*, by dividing a sufficient small sensitivity *S(r)*. However, such errors can be partly corrected by (a): replacing dividing sensitivity operation to the quotient between conjugate sensitivity and sensitivity modulus; (b) jointly solving Eq. (4) obtained from an array of receiver coils. Eq. (4) and (5) can be easily adapted for RRFCA reconstruction, by taking into account the varying sensitivity profiles for each T_{ACQ}. For RRFCA, the reconstruction matrix R_n for the *n*-th coil element (*n* = 1, 2 … *N*) is shown in Eq.(6). $S_n(r,t)$ is the sensitivity profile at the *r*-th location produced by the *n*-th element at time *t* (*t* = 1, 2 … *Y*, where *Y* is the number of phase encoding lines). The complete image from all receive channels can be combined with a sum-of-squares (SOS) approach.

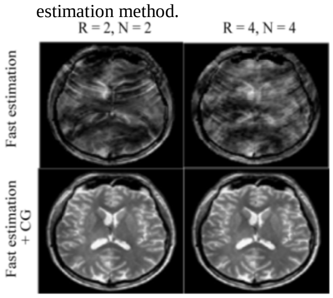

Fig.2 Acceleration study with multiple coils.

Results and Discussions: Fig. 1 demonstrates the reconstruction results with simulated data when RRFC and RRFCA were used in signal sampling. Compared with the result of direct inverse Fourier transform (top middle), the fast estimation (bottom left) has a dramatic improvement. It successfully removed most ghost artefacts, by accounting for the time-varying sensitivity in the reconstruction process. The remaining artefacts can be attributed to the loss of orthogonality in the reconstruction matrix. When using the fast estimation as the initial solution, the iterative conjugate gradient method produced an excellent image (top right). However, slight ghosting (red box) can still be observed. This may be owing to the relatively small coil size (35˚ open angle) and limited penetration. The fast estimation method was also studied when more rotating elements were introduced. The recovered images are shown in the bottom row, when the number of coils (*N*) = 2 and 4. The quality of the fast estimation was significantly improved, by eliminating ghosting artefacts and reducing intensity non-uniformity. The acceleration study with multiple coils was performed. As shown in Fig.2, the fast estimation with *N* = 4 has higher quality, despite the higher reduction factor, and better initial estimation also leads to a superior final image reconstruction. From Fig.3, it is clear that increasing the number of rotating elements can significantly improve the image quality. In terms of reconstruction time, with the help of initial image, a rotating array (4 elements) can reconstruct the image 6.8x faster (i.e. about 28 seconds) on the same commutating platform.

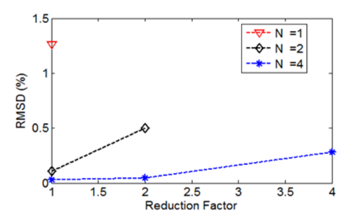

Fig.3 RMSD of final reconstructed image with different number of coils (N) and reduction factors.

Conclusion: A hybrid approach for image reconstruction with RRFCA working in stepping-mode was introduced. Excellent image reconstruction was presented with 4 coil elements at reduction factor of 4 in well less than a minute on a desktop computer, which illustrates the superior encoding capability of RRFCA and the efficiency of the proposed image reconstruction method. In the future, the encoding capability of RRFCA in RF transmission will be studied.

References: [1] A.Trakic, et al, *Concepts in Magn Reson Part B*, vol. 35B, 2009 [2] A.Trakic, et al, *Journal of Magn Reson*,vol 201,2009. [3] M. Li et al, 1117, *IEEE EMBC* 2012 [4] K. Pruessmann, et al, *Magn Reson in Med*, vol46, 1999. [5] K. Pruessmann, et al, *Magn Reson in Med*, vol46, 2001.