Ultra fast dynamic contrast enhanced time resolved UNFOLD imaging

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Introduction: The high sensitivity of MRI to contrast uptake by tumors has made Dynamic Contrast Enhanced (DCE) MRI an indispensable tool for tumor diagnostics. However, there is a trade-off between spatial and temporal resolution that results in sub-optimal image quality. To overcome this limitation, methods like keyhole [1], RIGR [2], TRICKS with parallel imaging [3] have been proposed. In the present work, we report a novel strategy of combining UNFOLD [4] with time resolved imaging to effect acceleration factors of 6 and higher. A new computationally efficient combined reconstruction strategy was also developed. Finally, the accuracy and performance of the new technique was tested on synthetic as well as DCEMRI data obtained from patients with liver and breast cancer.

Theory: UNFOLD has hitherto been used mainly for cardiac imaging. UNFOLD's dynamic FOV restriction to half the FOV was improved upon by using a novel sub-sampling strategy that increased the dynamic FOV to 0.7 FOV by moving the aliases to the corners of the FOV (arrows in Fig 5). This is a more optimal sub-sampling scheme for cylindrical, conical and spherical geometries (torso, breast, brain). If the TRICKS k-space scheduling is represented as ABACAB…, then UNFOLD sub-sampling yields $A_1B_1A_2C_1A_1B_2A_2C_2$… where the subscripts 1 and 2 refer to complementary sub-sampling of a region, phase shifted as per UNFOLD (see Fig 1). For reconstruction, we first performed UNFOLD on each annular region separately ($A_1A_2A_1A_2$...) after zeroing the other regions to estimate the missing k-space samples. UNFOLD filtering was performed with a Fermi filter retaining 80% of the bandwidth, after symmetrically replicating the data in time to reduce ringing. The data is now of the form ABACABAC… albeit in x-f space. The final step in reconstruction can be implemented in two ways. The x-f dataset can be Fourier transformed to obtain k-t data followed by a conventional linearly interpolated TRICKS reconstruction. A more efficient reconstruction can be obtained by an extended inverse Fourier transform of the filtered x-f data to obtain a sinc-interpolation, which is theoretically more accurate compared to linear interpolation. This also eliminates two costly 4D FFT operations.

Methods: All simulations and reconstruction were performed using MATLAB. A 3D model with two types of tumours- a 6 mm diameter tumour and a rim enhancing tumour with 6 mm diameter- was used to generate 128x128x24 3D k-space data sets. The tumours were made to enhance according to a pharmacokinetic model with an initial enhancement rate of almost 200% in the first minute, to model aggressively enhancing tumors [5]. Background enhancement and other small enhancing objects were also incorporated. Data on patients with cancer were acquired after obtaining informed consent on a 1.5 T GE Signa Excite scanner. Full k-space DCE-MRI data was acquired using a fat suppressed EC-TRICKS 3D spoiled GRE sequence [3] and then hexagonally under-sampled to obtain UNFOLD-TRICKS data. The scan parameters were as follows- acquisition matrix 256x192x36, bandwidth ± 62.5 KHz, TE/TR 1.4/3.9 ms, flip 15º, slice thickness 4.2 mm, 36x36 cm FOV. All dynamic scans were performed following administration of 10-15cc of Gadolinium contrast. Each annular segment was acquired in about 3.5s yielding a true temporal resolution of about 7s. With the UNFOLD-TRICKS combination, an acceleration factor of 6 was obtained (3-TRICKS, 2-UNFOLD). Conventional EC-TRICKS reconstructed images were compared with images obtained using the UNFOLD-TRICKS reconstruction described above. The tumour signal enhancement curves were computed to ascertain the accuracy of the method. Profiles through tumours were also computed to evaluate reconstruction errors and artifacts.

Results: To verify the feasibility of UNFOLD with DCE-MRI data, we performed analysis on real abdominal data and on simulated data. Results showed that UNFOLD can be successfully applied to DCE-MRI (data not shown due to space constraints). Fig.2 shows the central slice of the 3D phantom used for the simulations. Fig. 3 shows the signal enhancement curves for the rim-enhancing tumour (ROI 1 of Fig.2) obtained using our UNFOLD-TRICKS reconstruction vis-à-vis the "true" enhancement curve (TRICKS alone), showing very good agreement between the two. This is further corroborated by the near-identical profiles through the rim-enhancing tumor (Fig. 4). Figure 5 shows a slice from an UNFOLD-TRICKS reconstructed abdominal DCE-MRI data set. The diagonal dispersal of the aliases and the absence of artifacts can be clearly observed. Figure 6 compares enhancement curves obtained using the UNFOLD-TRICKS reconstruction with the TRICKS reconstruction for ROI 1 on Figure 5. Notice the improvement in temporal resolution reflected by a significant alteration in the slope of initial enhancement.

Conclusions: We have demonstrated the feasibility of obtaining acceleration factors of 6 and higher using a novel UNFOLD-TRICKS strategy. Analysis on synthetic and real DCE-MRI data was performed to validate the accuracy and temporal resolution increase obtained using the new technique. We expect the reconstructions to be more accurate than the conventional TRICKS reconstruction due to the superiority of the sinc interpolation. This technique can be easily combined with partial Fourier methods to further accelerate data acquisition.

References: 1) Plewes et al. ISMRM 1993; 1251. 2) Liang et al. IEEE TMI. Vol 13, pp 677-686 (1994) 3) Saranathan et al. Proc. ISMRM 13 (2005), 2206 4) Madore et al. MRM 42: pp 813-828 (1999) 5) Kuhl et al. Radiology; 211: pp 101-110 (1999)

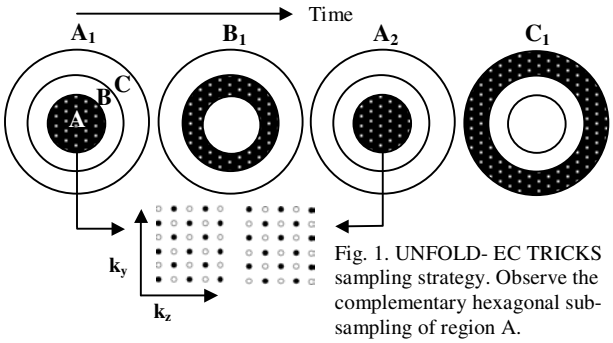

Fig. 1. UNFOLD- EC TRICKS sampling strategy. Observe the complementary hexagonal sub-sampling of region A.

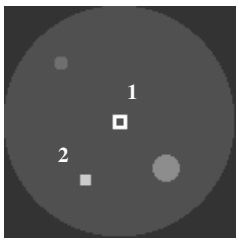

Fig. 2. A representative slice of simulated data. Also marked are the ROIs considered.

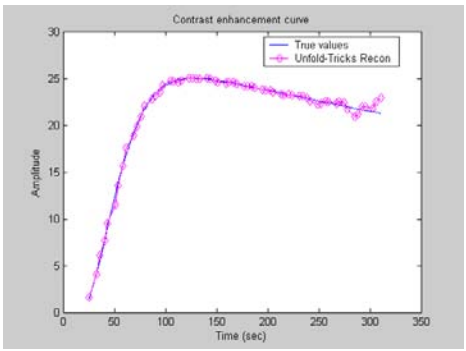

Fig. 3. Signal enhancement curve for ROI 1 (see Fig.2) obtained from combined UNFOLD-EC TRICKS reconstruction (by using the sinc interpolated UNFOLD reconstruction).

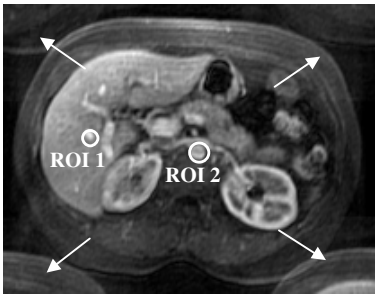

Fig. 5. A slice of the UNFOLD-TRICKS reconstructed 3D data set. The arrows show the direction in which the aliases have moved.

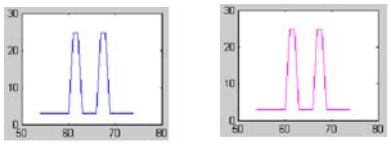

Fig. 4. The actual and reconstructed profile plots of one of the rows of ROI 1 (Fig. 2).

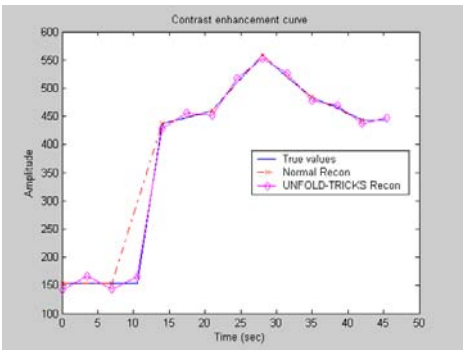

Fig. 6. Signal enhancement curve for ROI 1 (see Fig.5). Note the point missed in regular sampling, being picked by UNFOLD.