k-Space Channel Combination for Non-Cartesian Acquisitions Using Direct Virtual Coil (DVC) Calibration

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Introduction Maintaining acceptable reconstruction latency can be challenging when using a high number of receiver channels. For real-time imaging, images must be acquired and reconstructed with minimal latency which has led to recent interest in k-space channel combination using rapid non-Cartesian acquisitions [1,2]. k-Space channel combination reduces reconstruction latency because 1) memory requirements are reduced such that even large multi-channel 3-D datasets can be gridded during data acquisition, 2) channel combination can take place during image acquisition and 3) the number of Fourier transforms required to transform the data to image space is reduced from the number of channels to one.

The Direct Virtual Coil (DVC) calibration algorithm enables k-space channel combination with image quality comparable to image-space channel combination approaches [3,4]. In this work, we demonstrate that DVC-based channel combination can be combined with gridding to efficiently reconstruct multi-channel non-Cartesian data. The DVC calibration algorithm works by using low resolution multi-channel data to estimate the magnitude and phase of a 'virtual coil' image; least-squares fitting between the multi-channel data and virtual coil data is then used to generate channel combination kernels. To estimate the virtual coil phase, DVC uses an overlapping tile-based algorithm that has been shown to work with out-of-phase acquisitions and challenging coil geometries [5]. Combining DVC calibration with non-Cartesian imaging has the potential to make non-Cartesian k-space based channel combination more robust. The image quality of the proposed DVC-gridding approach is evaluated by comparing it to gridding each channel separately and combining the channel images in image space using sum-of-squares (SoS) channel combination.

Theory DVC calibration produces a small k-space convolution kernel for each channel. Applying these DVC kernels to the k-space data, followed by direct summation enables the multi-channel data to be combined to a single 'virtual coil' data set [3]. We propose combining the DVC kernels (via convolution) with the gridding kernel and then using the combined kernel to directly transform the non-Cartesian multi-channel k-space data to a single Cartesian k-space dataset. Since the gridding kernel is typically very finely sampled and the DVC kernel is in general non-separable, the combined kernel can require a fairly large matrix for storage, making in prohibitive for use in 3-D applications. To circumvent this challenge, we further propose that the kernels be stored separately and convolved on the fly as the data is gridded, as shown in Fig. 1. To make this approach possible, the DVC kernel must be designed with identical point spacing to the oversampled gridding matrix.

Methods MR data sets were reconstructed using a) standard gridding with SoS channel combination and b) DVC-gridding. For each dataset, difference images were computed and used to aid in image quality evaluation. All reconstruction routines were implemented in C++; all gridding was performed using a 1.25X oversampling factor and a 4x4 gridding kernel. For DVC, a 5x5 channel combination kernel was used, resulting in a DVC-gridding kernel size of 8x8 (convolution of the two kernels).

Three MR datasets consisted of 1) spiral acquisition of ACR-NEMA phantom with 8-channel cardiac coil; 2) radial SPGR brain scan with 32-channel head coil; 3) radial cardiac frame from a phase contrast acquisition using a 20-channel coil.

Results Image reconstruction results are shown in Fig. 2. The DVC-gridding results exhibit nearly identical SNR to the conventional SoS results. The main differences that can be seen in the reconstructions are 1) a reduction in background noise level for the DVC-gridding results and 2) a reduction in undersampling artifacts for the DVC-gridding results. These results are expected, since SoS channel combination is known to enhance background signal level by adding background noise in-phase [6,7] and the DVC channel combination kernels provide somewhat of a 'PILS' effect that reduces undersampling artifacts [8].

Discussion Results indicate that the DVC channel combination strategy can be combined with gridding to efficiently reconstruct multi-channel non-Cartesian data. Disadvantages of the proposed approach are 1) increase in combined kernel size lessens computational advantage to combining multi-channel data onto a single grid and 2) DVC calibration must occur before processing the data with the combined kernel. Even so, the proposed approach enables robust channel combination in k-space, which has the potential to appreciably reduce the reconstruction latency for multi-channel non-Cartesian acquisitions.

References (1) Chen et al., ISMRM 2008, p1296. (2) Wang et al., ISMRM 2010, p2883. (3) Beatty et al., ISMRM 2008, p8. (4) Beatty et al., ISMRM 2010, p2879. (5) Beatty et al., ISMRM 2010, p2892. (6) Roemer et al., MRM 1990 16:192-225. (7) Bydder et al. MRM 2002; 47:539-48. (8) Griswold et al, MRM 44:602-609.

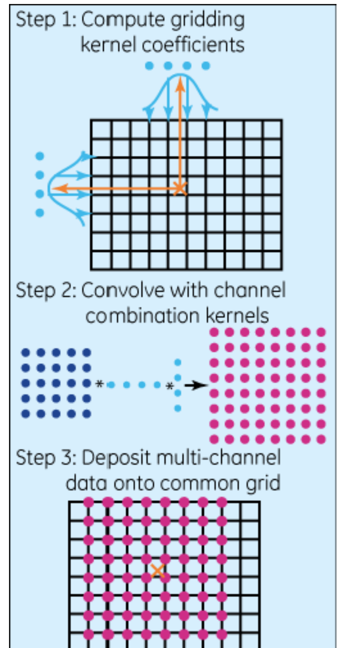

Figure 1: Convolving gridding and channel combination kernels on the fly.
During the gridding of each acquired k-space location, separable gridding kernel coefficients are computed and convolved with channel combination kernels to produce combined kernels. These combined kernels are then used to deposit multi-channel data onto a common grid. As shown, 5x5 channel combination kernels were used together with gridding kernels of width 4, resulting in 8x8 combined kernels.

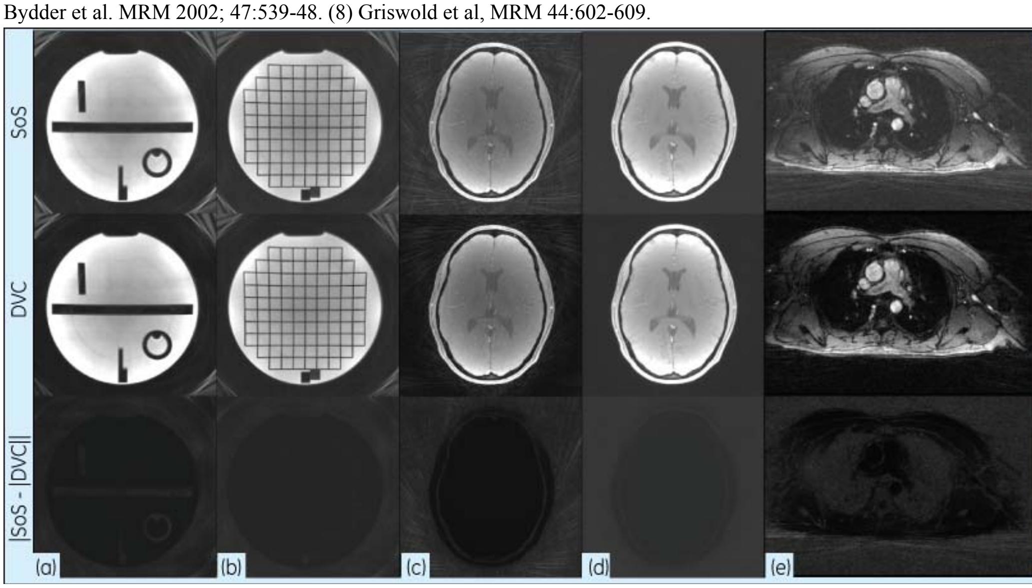

Figure 2 Results
Rows: 1) Sum-of-Squares results; 2) DVC gridding results; 3) difference images.
Columns: (a,b) ACR-NEMA phantom with spiral acquisition (8-channel); (c,d) SPGR brain scan with 'golden angle' full-spoke radial acquisition (32-channel); (c) 100 radial lines (d) 792 radial lines (e) Cardiac frame from phase contrast acquisition, radial (20-channel).
In regions of signal, the differences between the SoS and DVC reconstructions are negligible. Column (e) demonstrates the robustness of DVC calibration to magnetization phase; virtual coil phase shown in (f).

(f)