Parallel Imaging Based On Successive Convolution Operations (BOSCO)

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Introduction: Parallel imaging is a useful technique for fast MRI [1-6]. Recently, we introduced a new k-space-based parallel image reconstruction method based on successive convolution operations (BOSCO) [7]. It reconstructs un-aliased images by convolving the gridded k-space data from multiple channels with small convolution kernels (BOSCO kernels) and summing up the resultant k-space data. In this work, we report our progress on designing, implementing, evaluating and applying this technique.

Theory and Methods: BOSCO can be applied not only to non-Cartesian trajectories, as previous reported [7], but also to Cartesian trajectories. The first gridding step and the last deapodization step in non-Cartesian BOSCO are not necessary for Cartesian trajectories because the sampling points fall on the grid points. In Cartesian BOSCO, the outer k-space is under-sampled in the phase encoding (PE) direction and additional auto-calibrating scan (ACS) lines are acquired in inner k-space. The BOSCO kernels are calculated in the BOSCO training, where the inner k-space with the ACS lines is used for the target channel and the ACS lines are excluded from all the source channels, as shown in Fig. 1. In the Cartesian BOSCO reconstruction step, the entire partially under-sampled k-space data set from the source channels is convolved with the BOSCO kernels generated in the training and the resultant k-space data are summed up to suppress aliasing artifacts from the target channel.

The following experiments were performed to demonstrate BOSCO. **1)** Cartesian simulation data with different additive Gaussian noise in k-space was used to measure the SNR of the BOSCO images. **2)** As a demonstration of the effect of regularization, different regularization parameters were used in the reconstruction of the Cartesian simulation data set and the resulting SNR and artifact power were calculated as a function of the regularization parameter. **3)** Cardiac images were acquired on normal volunteers with different acceleration factors using a prototype 32-channel cardiovascular coil (InVivo, Gainesville, FL) and reconstructed using BOSCO. **4)** A comparison of GRAPPA [3] and BOSCO was performed by acquiring a 4X accelerated Cartesian data set using a Siemens head coil and reconstructing it using GRAPPA and BOSCO. **5)** A fully-sampled constant-density spiral data set was acquired and decimated to simulate under-sampled acquisitions. BOSCO reconstruction was performed on the decimated data set. **6)** To study the benefits of combining BOSCO with real-time imaging [8], a spiral SSFP sequence was designed to have a 5ms TR and 2.4ms spiral readouts. Constant density under-sampled spiral interleaves were acquired for each image frame and the training spiral readouts were acquired at the end of all the frames. The BOSCO kernels were trained using the training data set and the normal data set acquired immediately before the training data. The same BOSCO kernels were then used for other image frames during the reconstruction.

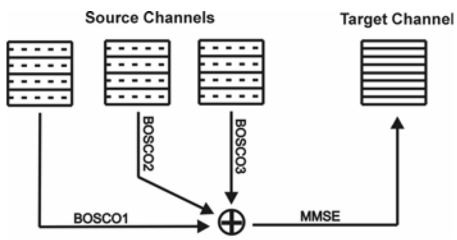

Fig. 1. BOSCO training for 2X accelerated Cartesian scans. All the data are inner-k-space data. Dashed lines represent additional ACS lines that are only included in the target channel but not in the source channels.

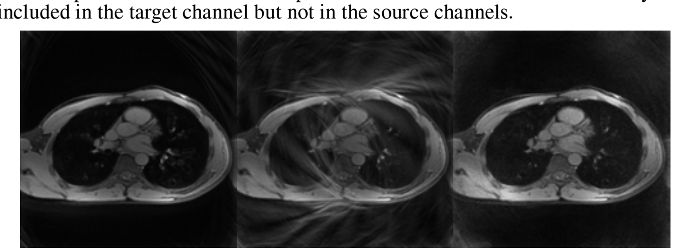

Fig. 4. BOSCO for a constant density spiral trajectory. The left, middle and right are the fully sampled reference image, under-sampled aliased image and un-aliased BOSCO image, respectively.

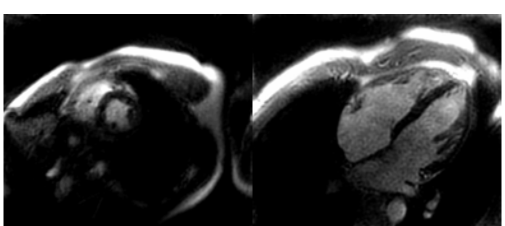

Fig. 5. Real-time BOSCO spiral images with different temporal and spatial resolutions. Left image has 20ms temporal resolution and 2.6mm spatial resolution. Right image has 40ms temporal resolution and 1.9mm spatial resolution.

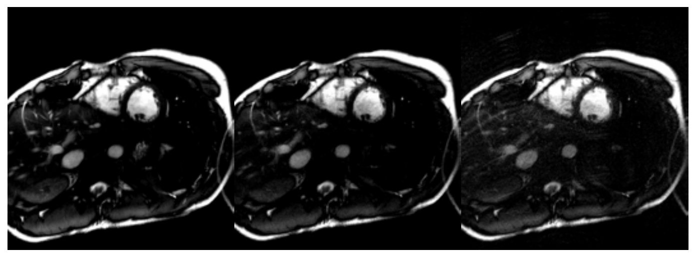

Fig. 2. BOSCO images with different acceleration factors for Cartesian trajectories in a breath-held ECG triggered cine scan. Left, middle and right are 2X, 4X and 6X accelerated images, respectively.

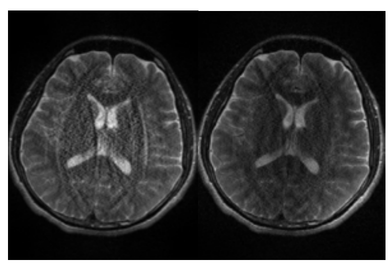

Fig. 3. A comparison of GRAPPA (left) and BOSCO (right) reconstruction for a Cartesian trajectory at 4X acceleration using the same raw data set. Both artifact level and noise amplification are reduced in the BOSCO reconstruction.

Results: The following are the results of the experiments mentioned above. **1)** BOSCO has an SNR efficiency (relative SNR/time) of 0.9849 and 0. 8950 for 2X and 4X accelerations, respectively, which are comparable to those of the GRAPPA technique [3]. **2)** Our simulation shows that BOSCO regularization can conveniently provide a trade-off between artifact suppression and noise reduction (not shown). **3)** Figure 2 shows cardiac BOSCO images with 2X-6X acceleration factors. As the number of available coil elements increases, BOSCO is capable of reconstructing images at higher acceleration factors with good artifact suppression. **4)** The 4X accelerated images in Fig. 3 show that the noise amplification and aliasing artifacts present in the GRAPPA image are reduced in the BOSCO image. **5)** Recently, we presented our results of BOSCO using variable density spirals [7]. In Fig. 4, we demonstrate that BOSCO can also be applied to constant density spirals with a separate low resolution scan used for training, which provides flexibility for the needs of different applications. **6)** Figure 5 shows real-time BOSCO spiral images with different spatial and temporal resolutions. With BOSCO, we were able to acquire and reconstruct real-time images with higher frame rate (25fps) than and comparable spatial resolution (1.9mm) to conventional breath-held ECG triggered cine scans.

Discussion: We show that BOSCO is a flexible, non-iterative and auto-calibrating parallel image reconstruction technique that applies to both Cartesian and non-Cartesian trajectories. This technique eliminates the need of multiple calibrations for different segments that is required in segmented GRAPPA techniques [4,5]. Two major differences between BOSCO and the existing k-space-based methods are that BOSCO is intrinsically a 2D method and the gridding convolution step is applied *before* any further processing of the data.

Conclusion: We demonstrated BOSCO as a valuable tool for different applications, including Cartesian parallel imaging scans, highly accelerated cardiac scans, constant density spiral imaging, and real-time imaging.

References: [1] Pruessmann et al., MRM 46:638-51 [2] Sodickson et al., MRM 38:591-03 [3] Griswold et al., MRM 47:1202-10 [4] Heidemann et al., MRM 56:317-26 [5] Heberlein et al., MRM 55:619-25 [6] Yeh et al., MRM 53:1383-92 [7] Hu et al., ISMRM 2005:10 [8] Nayak et al., MRM 46:430-35