BOSCO: Parallel Image Reconstruction Based on Successive Convolution Operations

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Introduction: Parallel imaging is a promising tool to speed up image acquisition [1-4]. In general, there are two types of techniques: image-space-based (e.g., SENSE) and k-space-based reconstructions (e.g., SMASH and GRAPPA). SENSE gives optimal SNR while reducing aliasing artifacts; however, it requires accurate coil sensitivity profiles, which are not available in some applications. In addition, for non-Cartesian acquisitions, SENSE necessitates the inversion of large scale matrices or multiple iterations to get an artifact reduced image, which is not suitable for some applications such as real-time imaging [8]. There have been several non-Cartesian GRAPPA reconstruction methods during the past few years [5-7]. We present a new auto-calibrating k-space-based parallel imaging method for non-Cartesian trajectories, which addresses the above mentioned problems. The acronym for the technique is BOSCO (parallel reconstruction based on successive convolution operations), because two successive convolutions – a gridding convolution followed by a BOSCO convolution -- form the basis of the technique.

Methods: The SMASH/GRAPPA techniques try to fit sampled data points from multiple coils to a missing data point, using the fact that multiple coil sensitivity profiles can be linearly combined to approximate a sinusoidal spatial distribution, effectively shifting the combined k-space data a certain amount in the phase-encoding (PE) direction. This fitting is equivalent to a convolution of the sampled data with a 1D kernel in the PE direction evaluated at the missing data point. This model works well for Cartesian trajectories, because all the data on one sampled PE line are shifted the same amount in the same direction. It is not straightforward to apply this model to non-Cartesian trajectories, because the required shift can be different from one point to another along the trajectory. Given the 2D nature of common non-Cartesian trajectories (i.e., they don't have separable PE and readout directions), in our method we convolve a small 2D kernel (BOSCO kernel) with each coil data and then linearly combine the results to form a composite k-space data set. Figure 1 shows details of how the data from multiple coils are combined. A variable sampling density is used so that the outer k-space is under-sampled while the inner k-space is fully sampled. In the first step, a gridding convolution is performed for each coil using a Kaiser-Bessel kernel so that each coil channel now contains data on grid points. In the second step, another 2D convolution is performed on each of the gridded coil data and all the convolutions are summed up in k-space to produce the composite k-space data for the target coil. In the third step, the composite data is then transformed to form an un-aliased image for that coil. As in GRAPPA, those two convolutions are repeated with each coil as the target, resulting in multiple un-aliased images with different sensitivity profiles, and all these coil images are combined in image space using square root of sum of squares to generate a final image with a relatively uniform sensitivity profile across the FOV. To determine the BOSCO kernel set for each target, the lower k-space is used for calibration similar to the way ACS lines are used for calibration in GRAPPA. Using the fully-sampled center of k-space, a 2D fit is performed from multiple coils to the target coil and the BOSCO kernel set that gives the best fit is used for later reconstruction of the whole k-space for the same target coil. As a separate set of BOSCO kernels is needed for each target, a separate calibration is performed for every target coil as well.

In vivo images of normal volunteers were acquired on a 1.5T Siemens Avanto scanner using a variable density spiral sequence with fully-sampled inner k-space and 2X under-sampled outer k-space. To investigate the effect of different acceleration factors on image quality, fully sampled constant density spiral in vivo data was also acquired and effective 2X/4X under-sampling in outer k-space was simulated by only including every second/fourth spiral interleaf of outer k-space in the reconstruction. The BOSCO reconstruction algorithm was implemented using Matlab (Mathworks, Natick, MA, USA) on an IBM Linux cluster.

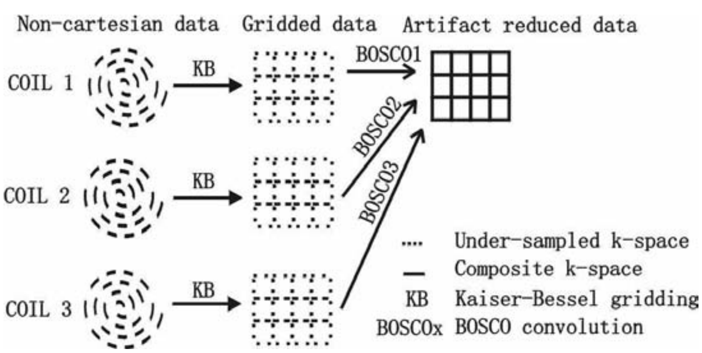

Figure 1: BOSCO reconstruction scheme. Non-Cartesian k-space data is first gridded to Cartesian points using a Kaiser-Bessel convolution kernel. A second convolution (BOSCO convolution) is performed for each coil to form a composite artifact-free k-space for one coil. The BOSCO kernels are determined by BOSCO training using the center of k-space. This process is repeated for every coil.

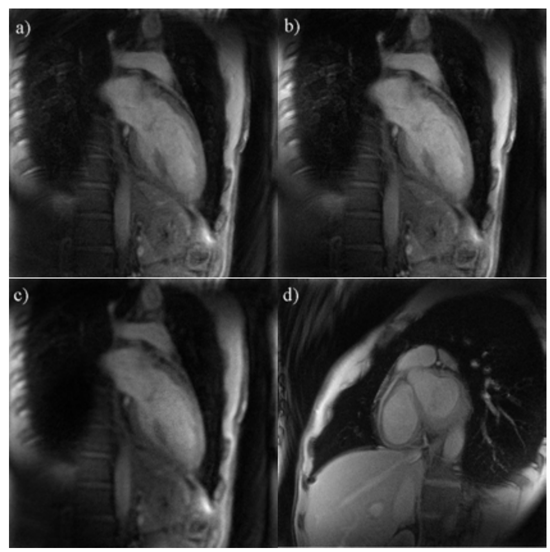

Figure 2: Coronary artery images acquired on normal volunteers. a) Reference image reconstructed using fully sampled k-space. b) BOSCO image reconstructed with an acceleration factor of two. c) BOSCO image at the same orientation as b, with acceleration factor of four. d) BOSCO image reconstructed using variable density spiral k-space data with an under-sampling factor of two in outer k-space. All the above BOSCO images are free of aliasing artifacts.

Results: Figure 2 shows cardiac images reconstructed using BOSCO. Compared to the reference image (Figure 2a) that is reconstructed by simply combining the magnitudes of fully-sampled coil images using square root of sum of squares, the BOSCO images (Figure 2b and 2c) are virtually aliasing free for acceleration factors of two and four. The Figure 2d) image shows a BOSCO image of the RCA using the variable density spiral sequence with an under-sampling factor of two in outer k-space. The SNR in BOSCO images decreases when using larger

Discussions: BOSCO can be seen as a generalized k-space based parallel reconstruction that potentially can be applied to arbitrary k-space trajectories. The k-space based parallel imaging techniques so far, such as SMASH and GRAPPA, try to use acquired sampling points from multiple coils to approximate one single un-acquired sample point in k-space. On the other hand, BOSCO uses acquired k-space from multiple coils to approximate the whole target k-space. The non-Cartesian GRAPPA implementations so far also include two convolutions: a 1D GRAPPA convolution followed by a gridding convolution. The BOSCO method, on the other hand, does the gridding convolution first before the 2D BOSCO convolution, which should be reasonable given that convolutions are commutative. Since BOSCO only involves convolutions of k-space data with relatively small kernel sizes (5x5 for the image shown above) that can be quickly performed once the kernels are determined, it requires much less computation than a non-Cartesian SENSE reconstruction, which makes it suitable for applications such as real-time imaging. BOSCO is fully auto-calibrating, eliminating the need for measuring accurate sensitivity maps, which can be difficult in some applications.

Conclusion: We demonstrated the initial feasibility of BOSCO parallel reconstruction for non-Cartesian k-space trajectories. More studies are needed to determine the selection of reconstruction parameters, such as kernel size and image combination schemes, and to optimize the SNR performance. Spiral BOSCO produces artifact-free images of the coronary arteries at acceleration factors of at least four and should be suitable for real-time imaging, with the BOSCO kernels calculated once.

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[7] Heberlein et al, Proc ISMRM 2004:328 [8] Nayak et al, MRM 46:430-435(2001)