

# Slice-Localized Soft-Gating for Non-rigid Motion Correction in Free-Breathing 3D Cartesian MRI

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**PURPOSE:** Free-breathing MRI increases scan efficiency without unnecessary strain for the patient. In such a scheme, respiratory motion must be considered. Soft-gating<sup>[1]</sup> (or motion-based weighting) is a straightforward approach that reduces motion artifacts. However, the performance of soft-gating depends on the accuracy of the motion-based weights. Thus, we propose a novel approach in calculating and in applying the weights for soft-gated 3D Cartesian imaging with spatial localization.

**METHOD:** Respiratory motion is non-rigid; the degree of motion varies in space. By exploiting the localized sensitivity of each element in a coil array, navigators can measure localized motion<sup>[2]</sup>. For 3D Cartesian imaging, spatial localization in 1D can also be obtained by transforming the raw k-space data into the hybrid  $(x, k_y, k_z)$ -space – with an inverse 1D-FFT along the fully-sampled readout-direction,  $x$ . Assuming no motion during a single readout, the hybrid-space formulation decouples each  $x$ -slice. As a result, all reconstruction operations will be performed on a slice-by-slice basis.

**Algorithm:** For each  $x$ -slice, the following operations are performed: Geometric coil compression<sup>[3]</sup> is applied to compress the multi-channel data ( $N_c$  channels, indexed with  $c$ ) to a reduced set of virtual coils ( $N_v$  channels, indexed with  $v$ ). All virtual coils are linear combinations of the multi-channel data. The first virtual coil ( $v=1$ ) constructs a sensitivity map that is as uniform as possible. Thus, the compression weights  $s(x, c, v=1)$  are applied to the navigator data. This compressed navigator data are then used to derive motion-based weights,  $w(n, x)$ . A threshold is set; any motion greater than the threshold is exponentially weighted down. These weights describe the inconsistency of the data from motion during the  $n$ -th TR, where  $w(n, x) = 1$  signifies motion-free data and  $w(n, x) = 0$  signifies highly inconsistent data. Finally, these weights are used to soft-gate the reconstruction. A summary is shown in Fig. 1.

**Setup:** Variable-density sampling with radial view-ordering (VDRad)<sup>[4]</sup> was used to help make motion artifacts incoherent. To generalize the approach, a simple navigation method was used: the readout was extended to sample the DC signal of the refocused FID. The average magnitude of this DC signal described the patient's motion<sup>[5]</sup>. Soft-gating was incorporated into L<sub>1</sub>-ESPIRiT, a compressed sensing & parallel imaging algorithm<sup>[6]</sup>. Reconstruction was performed in MATLAB/C++. For comparison, soft-gating with a single set of weights was applied.

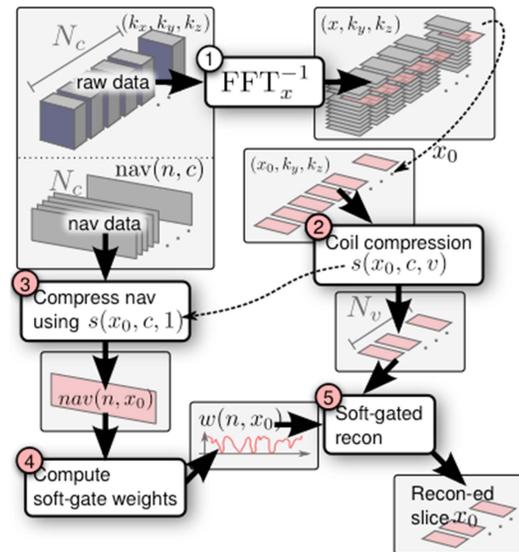
**Experiments:** Free-breathing abdominal scans were performed on pediatric subjects in a 3T GE MR750 scanner using a 32-channel cardiac coil. 3D spoiled-gradient-recalled sequence with a spectrally selective fat-inversion pulse (TI = 9 ms), TE/TR = 1.2/3.0 ms, flip angle = 15°, and bandwidth = ±100 kHz were used to acquire the post-intravenous-contrast-injection scans in the coronal orientation.

	Study 1	Study 2
Resolution	1.1×1.6×2.2 mm <sup>3</sup>	1.1×1.5×2.4 mm <sup>3</sup>
Field of View (FOV)	36×28.8×17.6 cm <sup>3</sup>	34×27.2×16.3 cm <sup>3</sup>

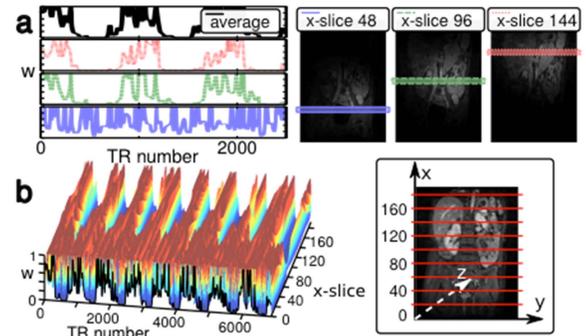
**RESULTS:** Soft-gating reduced motion artifacts: reducing blurring and aliasing artifacts (Fig. 3). The  $x$ -slice specific weights (Fig 2) were more effective in reducing motion corruption, as seen by an increase in hepatic vessel sharpness, liver dome sharpness, and reduction of noise (aliasing energy) compared to using single weights.

**DISCUSSION:** By applying  $x$ -slice specific weights instead of a single set of weights, the derived weights can be better catered to each specific  $x$ -slice. The difference will be more dramatic when there are different types of motion throughout the FOV. Also, the resulting spatial sensitivity of the compressed navigators still covers a large region (Fig. 2). This method can be further improved with better spatial localization.

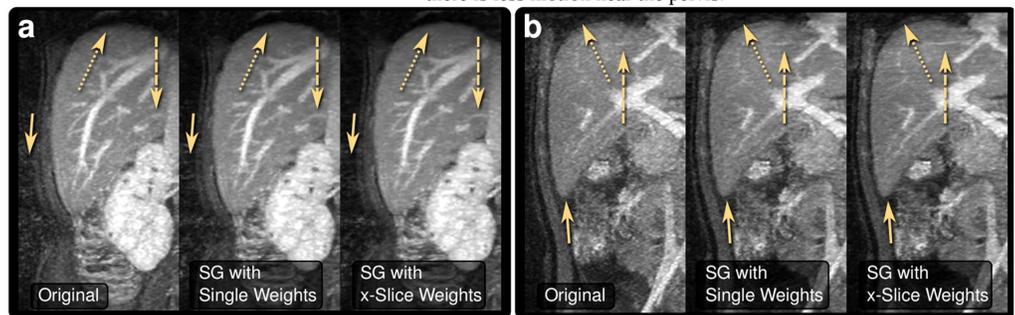
**REFERENCES:** [1] KM Johnson et al, MRM 67: 1600-1608, 2012. [2] JY Cheng et al, MRM 68: 1785-1797, 2012. [3] T Zhang et al, MRM 67: 571-582, 2012. [4] JY Cheng et al, ISMRM Data Workshop, 2013. [5] AC Brau and JH Brittain, MRM 55: 263-270, 2006. [6] M Uecker et al, MRM 2013 (e-print).



**FIG. 1: Method overview.** (1) Multi-channel data is first transformed into the hybrid  $(x, k_y, k_z)$ -space. (2) Geometric coil compression<sup>[3]</sup> is applied to the data. (3) Compression weights for the first virtual coil are used to compress the navigator data. (4) Soft-gating weights are computed and (5) used to reconstruct the particular  $x$ -slice. Steps (2-5) are repeated for each  $x$ -slice.



**FIG. 2: Soft-gating weights for Study 1.** **a:** Average weight (black) and  $x$ -slice specific weights for  $x$ -slices 48 (blue), 96 (green), and 144 (red). **b:** Motion-based weights of all  $x$ -slices. After coil-compression weights for the first virtual coil are applied to the navigator data, a degree of spatial localization is achieved. The corresponding coil sensitivity maps and  $x$ -slice locations are shown on the right in **a**. More weights are closer to 1 in the lower  $x$ -slices; there is less motion near the pelvis.



**FIG. 3: Results.** **a:** 11-slice-MIP of a 6-yr-old female. **b:** 4-yr-old female. With soft-gating (SG) using a single set of weights (average of all weights), the liver dome (dotted in **a**), liver wall (dotted in **b**) and the fine hepatic vessels (dashed in **a** and **b**) are sharpened. By applying  $x$ -slice specific weights, motion artifacts are further reduced: sharpening of structures in **b** (solid & dashed) and even recovery of the fine diaphragm structure (dotted in **b**). Compared to the original, the average aliasing energy (solid in **a**) is decreased by a factor of 0.72 for single weights and by 0.58 for  $x$ -slice specific weights.