Free Breathing Diagnostic Contrast Enhanced 3D MRI with Resolved Respiratory Motion
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PURPOSE: Respiratory motion is a major issue in abdominal MRI, especially for pediatric patients who have difficult performing breath-holds. The problem is exacerbated in lengthy scans, such as for dynamic contrast enhanced (DCE) MRI. Much of the previous work has been focused on reducing respiratory motion artifacts through reconstruction correction schemes. An alternative approach is resolving the motion. This approach has been previously proposed11 where both cardiac and respiratory motion were resolved. Here, we adopt a similar approach to correct for respiratory motion in free breathing DCE-MRI by extending the data-acquisition space to an additional respiratory dimension and exploiting data redundancy to constrain the reconstruction.

METHOD: The discretized data consists of 5 dimensions: spatial (x,y,z), dynamic contrast nDCE, and respiratory state nresp. The scan acquisition is temporally constrained, especially for pediatrics, since most of the contrast dynamics occurs within 2 min after injection. Thus, the exam must be highly accelerated. Fortunately, redundancy improves with increasing dimensions21. Much like images are more redundant than audio and video more than images, our 5D-space is highly redundant.

Algorithm: For each TR, discrete values for nDCE and nresp are assigned to the corresponding readout. Time is segmented into nDCE discrete bins for the nDCE-dimension. Measured motion (with Butterfly33) is segmented into nresp discrete bins for nresp (Fig. 1). Images are reconstructed using CS-enhanced parallel imaging (PI). Given differing dynamics in nDCE and in nresp different sparsity models are applied. The locally low-rank (LLR) constraint is used in the nDCE-dimension. The total variation (TV) penalty is used in the nresp-dimension. The problem is a recovery of the 5D-image m from acquired k-space data y:

\[
\arg\min_m |Am - y|_2 + \lambda_1 J_{\text{resp}}(m) + \lambda_2 J_{\text{DCE}}(m) \quad \text{where} \quad J_{\text{resp}}(m) = \|D_{\text{resp}}m\|_1 \\
J_{\text{DCE}}(m) = \sum_{n_{\text{DCE}}} \sum_{n_{\text{resp}}} \|C(b,n_{\text{resp}})m\|_1,
\]

Matrix A consists of linear operations: applying the coil-sensitivity maps, taking the Fourier transform, and selecting the acquired samples. Function Jnresp(m) is the TV penalty in nresp-dimension where Dn is a finite difference operator in dimension n. Function JnDCE(m) exploits LLR in nDCE-dimension where b is a block in the spatial-dimension (we used a block size of 16x16). C(b,nresp) is the operator that reorders this block from a particular nresp into a spatiotemporal matrix, and \(\|\|\|\) is the nuclear norm of matrix x. Regularization parameters \(\lambda_1\) and \(\lambda_2\) are experimentally tuned.

Setup: Data were acquired using variable-density sampling and radial view-ordering (VDRad)77. Motion was measured using intrinsic navigation with the Butterfly33 modification to a 3D Cartesian spoiled GRE sequence. Fat suppression was achieved using a spectrally selective fat-inversion pulse (TI = 9 ms). Coil sensitivity maps were estimated using ESPiRiT86. Our approach was compared to (1) soft-gated83 LLR of a DCE11 reconstruction and (2) L1-ESPiRiT86 of a lightly undersampled post-contrast scan.

Experiment: A 4-yr-old female was scanned on a 3T GE MR750 scanner using a 32-channel cardiac coil. Contrast was intravenously injected for the 2.7-min scan. The data were divided with nresp = 8 and nDCE = 18 (temporal resolution = 8.8 s). Specific scan parameters include TE/TR = 1.3/3.2 ms, flip angle = 15°, resolution = 1x1.4x2 mm, FOV = 32x25.6x16 cm2, and bandwidth = ±100 kHz.

RESULTS: With respiratory-motion-resolved DCE-MRI, similar contrast dynamics were achieved compared to the DCE-only reconstruction. Our proposed approach yielded slightly sharper images due to the added TV penalty. Also, the acceptance window for respiratory motion in our method is much more strict through data binning. This strictness can be tolerated because of the additional nresp to exploit sparsity conditions. Also, similar respiratory-motion dynamics were achieved compared to the post-contrast scans. The post-contrast scans resulted in slightly better image quality due to higher SNR from lower acceleration factors.

DISCUSSION: Computation is an issue for high-dimensional images. Fortunately, 3D Cartesian imaging enables slice-by-slice reconstruction along the fully encoded readout axis. This reduces the process to smaller and parallelizable 4D problems. Spatial sparsity, such as with spatial Wavelet transform33, can also be incorporated to further constrain the optimization at the cost of added computation. Lastly, the nresp-dimension may provide more diagnostic information. Further investigation is required.


FIG. 1: Data binning. The acquired data is separated into nDCE and nresp bins. The entire scan is segmented by time into nDCE different nDCE-bins. The respiratory motion is used to divide the data into nresp separate nresp-bins. Here, nDCE = 8 and nresp = 4. Different bins can have very different acceleration factors.

FIG. 2: Free breathing DCE-MRI of a 4-yr-old female. a: Comparison of DCE-MRI using soft-gated LLR (first column), motion-resolved DCE-MRI using proposed method (3 nresp-states shown in other columns), and post-contrast motion-resolved imaging using conventional PI/CS (last row). b: Cross-section from a single nDCE illustrating the resolved respiratory motion (cross-sections are repeated to emphasize the periodic nature). Select time points are shown focusing on the enhancement of the kidney in the nDCE-dimension (nDCE corresponds to the actual time) and respiratory motion in the nresp-dimension. The effective acceleration factor R is displayed on the bottom corner of each image. Note the ability to depict comparable contrast dynamics and respiratory motion despite the high acceleration factor with our proposed approach.