Variable-Density Radial View-Ordering and Sampling for Time-Optimized 3D Cartesian Imaging

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PURPOSE: High-resolution volumetric imaging is sensitive to patient motion due to its long scan times. Depending on the k-space sampling trajectory, motion artifacts may appear as ghosting, blurring, and/or additive noise. Given the robustness of Cartesian imaging to off-resonance and other system errors, we focus on ordering the \( (k_x, k_y) \)-views in 3D Cartesian imaging. We present a novel method to order and sample the \( (k_x, k_y) \) Cartesian grid that is robust to motion effects and ideal for compressed sensing (CS) & parallel imaging (PI). We propose the variable-density radial view-ordering and sampling (VDRad) strategy.

METHOD:

1. Setup:
   a. For each view to collect, determine the \( (k_x, k_y) \) value: k-space radius, \( k = k_x + k_y \), is adjusted for uneven acceleration and k-space angle, \( \phi = \arcsin(k) \), is adjusted to incorporate a spiral twist.
   b. Given a desired spoke length \( L \) (each spoke is made up of \( L \) views), determine the number of spokes necessary to achieve the desired acceleration to form 1 temporal phase.

2. Ordering:
   a. Order the samples first by the k-space radius and second by the k-space angle.
   b. Divide the ordered views into \( L \) rings where the number of points in each ring is proportional to the k-space magnitude (Fig. 1b).

3. Sampling for each ring: Using the k-space angle, sample and order each view according to the golden-angle [1,2]: \( 360^\circ / \phi \approx 137.5^\circ \) where \( \phi = (1 + \sqrt{5})/2 \). See Fig. 1c.

4. Final re-ordering:
   a. Build spokes by selecting the n-th sample in each ring.
   b. For each spoke, the samples can be re-ordered for special considerations. For instance, the samples can be re-ordered for optimal smoothness to minimize eddy current.

EXPERIMENT: All scans were performed on a 3T GE MR750 scanner using a 3D spoiled gradient echo sequence with flip angle = 15° and bandwidth = ±62.5 kHz. Motion was measured using Butterfly navigation [3]. All images were reconstructed using ESPRIT [4], a CS & PI reconstruction algorithm. In vivo scans were performed free-breathing. See table for specific scan parameters.

<table>
<thead>
<tr>
<th>TE/TR [ms]</th>
<th>Resolution [mm³]</th>
<th>FOV [cm³]</th>
<th>Navigation time per TR [ms]</th>
<th>Coil receiver</th>
<th>Acceleration factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phantom</td>
<td>1.7/4.6</td>
<td>1.2 × 1.2 × 3.0</td>
<td>30 × 24 × 21.6</td>
<td>0.14</td>
<td>30-ch cardiac</td>
</tr>
<tr>
<td>Abdominal 1</td>
<td>1.4/3.9</td>
<td>1.0 × 1.3 × 3.0</td>
<td>34 × 27 × 21.8</td>
<td>0.096</td>
<td>32-ch torso</td>
</tr>
<tr>
<td>Abdominal 2</td>
<td>1.4/3.6</td>
<td>0.88 × 1.4 × 2.0</td>
<td>29 × 24 × 16.4</td>
<td>0.12</td>
<td>32-ch torso</td>
</tr>
</tbody>
</table>

RESULTS: The single temporal phase reconstruction of the phantom (Fig. 3a) demonstrated that the sampling mask is appropriate for CS & PI. Motion was introduced during the scan (Fig 3b), and a motion-free image (Fig. 3c) was successfully obtained by incorporating data-consistency weights [5] in the ESPRIT algorithm. Lastly, with VDRad, we were able to reconstruct high-resolution motion-free images from free-breathing scans (Fig 4) using the weighted ESPRIT algorithm with motion autofocusing [3].

DISCUSSION & CONCLUSION: Our proposed method is an alternative to motion compensated view-ordering, such as ROPE [6] and PAWS [7]. In our method, scan efficiency is partially sacrificed for ease of implementation and robustness to all types of motion. The radial path and golden-angle ordering ensures that k-space is evenly covered even if acquisitions must be discarded. Additionally, for multi-phase imaging, each phase will have a sufficiently different sampling pattern. Lastly, the variable-density sampling ensures an ideal undersampling point-spread-function for CS & PI reconstructions. Some ideal applications for the sampling/ordering include retrospective gating and dynamic contrast enhanced abdominal MRI.