Five-Dimensional Free-Breathing Cardiac MRI Using a 3D Cones Trajectory

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Introduction: Conventional methods for imaging cardiac function seek to suspend or effectively eliminate respiratory motion to avoid image artifacts. However, in many disease states, including pericardial constriction and diastolic dysfunction, it is precisely the changes in cardiac function associated with changes in respiration that can reflect the pathophysiology and should be studied. In this work, we present a rapid and comprehensive free-breathing technique for capturing the 5-dimensional (5D) physiologic state of the heart, including 3D spatial information, 1D cardiac phase information, and 1D respiratory phase information. Data is collected using the 3D cones readout trajectory [1, 2] to provide 4-fold scan time reduction (compared to 3D Cartesian encoding), improve robustness to motion/flow effects, and suppress undersampling artifacts.

Methods: Acquisition: The 3D cones trajectory covers a spherical volume in *k*-space with a set of nested conical surfaces which are sampled by spiraling readouts (Fig. 1a). The full set of cone readouts is divided into interleaved segments (Fig. 1b) and acquired with a continuously running SSFP sequence (Fig. 1c) (not synchronized to any gating signal). Pairing of adjacent readouts mitigates eddy current effects (Fig. 1b) [3]. Each segment is collected multiple times to fully sample the cardiac and respiratory cycles before moving on to the next segment. Physiologic signals from the respiratory bellows and peripheral pulse oximeter are recorded.

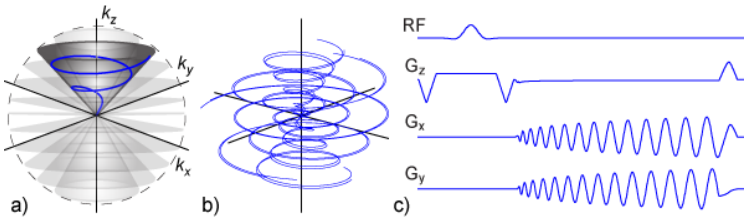

Fig. 1. (**a**) 3D cones trajectory. (**b**) Acquisition segment consisting of 10 readouts. Note the pairing of adjacent readouts. (**c**) SSFP cones imaging sequence.

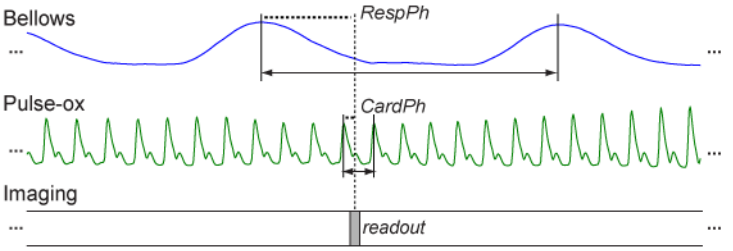

Fig. 2. The respiratory phase (*RespPh*) and cardiac phase (*CardPh*) of each readout are retrospectively determined from the recorded physiologic signals. Acquired data are then re-binned and reconstructed to obtain a 5D image matrix.

Reconstruction: Based on the recorded physiologic signals, the respiratory and cardiac phases of each cone readout are retrospectively determined from the readout's relative temporal position within the local respiratory and cardiac cycles (Fig. 2). The number of respiratory and cardiac phases to reconstruct are quantized to ($T_{RespAvg}$ / $T_{CardAvg}$) and ($T_{CardAvg}$ / T_{Seg}), respectively, where $T_{RespAvg}$ is the average respiratory cycle duration, $T_{CardAvg}$ is the average cardiac cycle duration, and T_{Seg} is the duration of one acquisition segment. Data are re-binned into a multi-dimensional matrix according to this information. View sharing is done for the last/first cardiac phases and last/first respiratory phases, assuming periodic motion. Missing data are zero filled. 3D gridding is then performed to reconstruct an entire 3D volume for each respiratory and cardiac phase combination (temporal resolution is T_{Seg} for each cardiac phase and $T_{CardAvg}$ for each respiratory phase). Data from multiple coils are combined by a sum of squares.

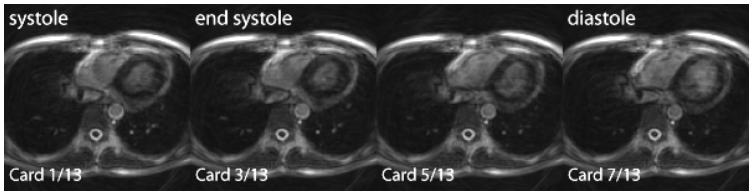

Fig. 3. Multiple cardiac phases of slice 5/10 at respiratory phase 5/9 (end expiration).

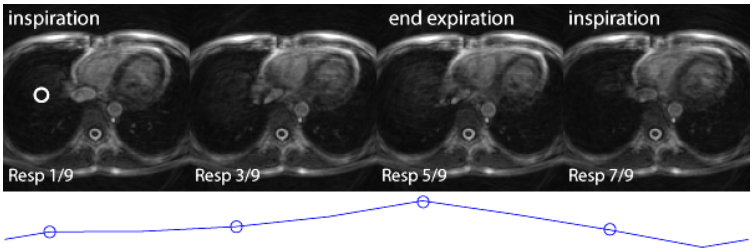

Fig. 4. Top: Multiple respiratory phases of slice 3/10 at cardiac phase 8/13 (mid-diastole). **Bottom:** Magnitude of ROI (white circle on Resp 1/9 image) for each respiratory phase. Notice how S/I motion of the liver/diaphragmatic interface is captured in the images and highlighted in the ROI magnitude trace.

Experiments: Setup: Axial free-breathing cardiac scans were performed on a GE Signa 1.5 T Excite system using an 8-channel cardiac array. An FOV of 24x24x8 cm^3 and resolution of 2x2x8 mm^3 (120x120x10 matrix) were encoded using 300 cone readouts (4-fold acceleration vs. 3D Cartesian), divided into 30 segments of 10 readouts each. T_{Seg} was 50 ms (SSFP TR = 5 ms). Each segment was acquired 100 times and total scan time was *2 min 30 sec*.

Results: Figures 3 and 4 show the 5D data obtained from a healthy volunteer, which was reconstructed at 13 cardiac and 9 respiratory phases ($T_{CardAvg}$ = 646 ms, $T_{RespAvg}$ = 5652 ms). After re-binning and view sharing of last/first phases, 88% or more of the 300 readouts were available for each cardiac and respiratory phase combination. Fig. 3 displays several cardiac phases of slice 5/10 at end expiration, which is essentially a conventional cardiac cine with respiratory motion eliminated. Alternatively, Fig. 4 shows resolved respiratory phases for slice 3/10 at mid-diastole, along with a signal trace highlighting S/I motion of the liver/diaphragmatic interface caused by respiration.

Discussion: We have demonstrated a comprehensive technique for capturing a 5D view of the heart in its natural free-breathing state. The 3D cones provide 4-fold acceleration vs. 3D Cartesian to make collection of this large dataset possible within a clinically feasible duration (*2 min 30 sec*). Absence of a small fraction (<12%) of non-Cartesian cone readouts in this 5D dataset manifests as incoherent low-amplitude artifacts that are more tolerable than coherent aliasing in Cartesian undersampling. This 5D dataset can be reformatted to provide conventional cardiac cines at multiple respiratory phases, or more interestingly, "respiratory cines" at various cardiac phases. Volume measurements may be performed on this 5D dataset to quantitatively assess cardiac function with respect to respiration and study various disease states.

References: [1] Gurney PT, et al., MRM 2006; 55: 575-582. [2] Gurney PT, PhD Thesis, Stanford University, 2007. [3] Bieri O, et al., MRM 2005; 54: 129-137.