Retrospective motion-adapted smart averaging for free-breathing cardiac MRI

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Introduction: A pencil beam navigator with 2D selective excitation, placed on the right hemidiaphragm, is commonly used in cardiac imaging to suppress respiratory motion [1]. However, prospective navigator gating has several limitations including drift and lengthy nondeterministic acquisition time. Furthermore, since the diaphragm navigator can give only a partial (and noisy) information on the displacement of the heart, motion errors at higher spatial resolution cannot be reduced indefinitely by selecting an ever smaller gate, even if the increased scan time were acceptable. Retrospective motion correction, as in [2], is also limited by the precision of the navigator. The center of k-space must be acquired when the heart is close to the reference position to avoid severe motion artifacts, whereas higher frequencies are more forgiving. This effect was used to design a motion-adapted gating method in [3], but current reconstruction methods do not exploit this variable sensitivity of k-space to motion. We propose to compensate for respiratory motion using a weighted average of multiple k-space acquisitions, with weights determined by the predicted motion-induced errors. This technique allows us to acquire images with a large gating window and retrospectively correct for respiratory motion using all the acquired data.

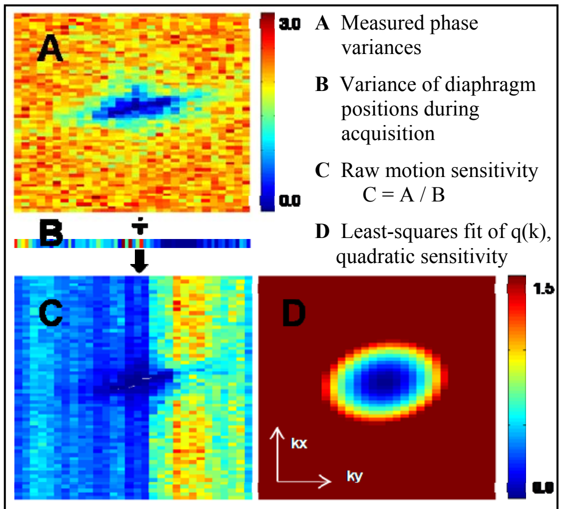

Fig 1: A subject-specific model (D) of sensitivity of phase errors to the diaphragm position gives weights for an averaging rule that makes more efficient use of multiple acquisitions than retrospective gating. (kx = freq. encode, ky = phase encode).

Theory: To first order, the respiratory motion is a translation, so it contributes primarily to the phase errors. We create a subject-specific model of the sensitivity of the phase at each spatial frequency to the diaphragm motion. This is done by finding the ratio of the variance of the phase at a point in k-space, computed over multiple acquisitions, to the variance of the diaphragm positions corresponding to those acquisitions (Fig 1A-C). If phase errors did not wrap around 2π, this ratio would be approximately quadratic in since the phase errors are linear in *k*. Thus, we perform a least-squares fit of a quadratic function to this ratio in the center of k-space (Fig 1D), where this wrapping occurs infrequently. A separate motion model is fit for each coil image. We then average the phases with weights given by , where is the displacement of the diaphragm from the reference position at the time when average *i* of the current line was obtained, and is a small constant chosen to yield smooth weights as . The effect of this scheme is similar to gating in outer k-space and averaging in central k-space. The errors present in the magnitude data are assumed to be uncorrelated with the respiratory motion, so the magnitudes are averaged with equal weights.

Method: Data were acquired on a 1.5T Philips Achieva scanner with the body coil for the phantom study and a 5-channel cardiac coil for the *in vivo* study. For the 2D phantom study, the spatial resolution was 2×2 mm^2 with a 10 mm slice. Images were acquired using multi-shot with 30 phase-encode lines per shot, centric phase-ordering, and manual motion of the phantom after every two or four shots. Each average required four shots to complete, and 20 averages were obtained. The range of motion was 3 cm along the frequency encode (k_x) direction, which produced ghosting as seen in (Fig 2a). A 2D navigator was placed on the top edge of the phantom to measure the motion in the frequency encode direction. The *in vivo* study consisted of 3D coronary-targeted scans of four healthy adult subjects with an ECG-triggered SSFP sequence (TE/TR/α=4.3/2.1/90°). The spatial resolution was 1×1×3 mm^3. The navigator was placed on the dome of the right hemidiaphragm. For each subject, 7-10 averages were acquired with a gating window of 50 mm (i.e. 100% gating efficiency). Images were reconstructed offline in Matlab and evaluated using a subjective score of 1-4 (1=excellent, 4=poor).

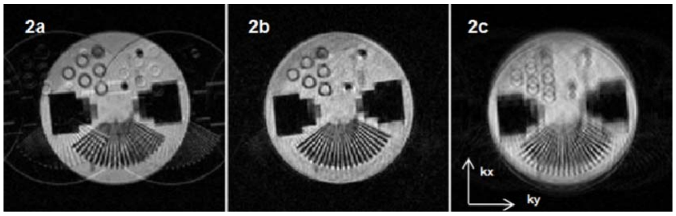

Fig 2: Phantom acquired with inter-shot motion along the kx direction: a) retrospective gating with a 5mm gate, b) motion-adapted average of 3 acquisitions, c) unweighted average of 3 acquisitions.

Results: Figures 2 and 3 each show three reconstructions using retrospective 5mm navigator gating, our weighted average of 3 ungated acquisitions, and an unweighted average. In a blinded comparison of the four *in vivo* reconstructions by two readers, motion-adapted averaging scored 1.9, slightly worse than gating (1.8) (P=NS), but the proposed method significantly outperformed simple averaging, which received a mean score of 2.9 (P<0.05).

Conclusions: We have presented a novel method to combine images acquired from multiple-averages exploiting the sensitivity to motion of the different spatial frequencies. This technique allows efficient combination of multiple averages using respiratory navigator signals.

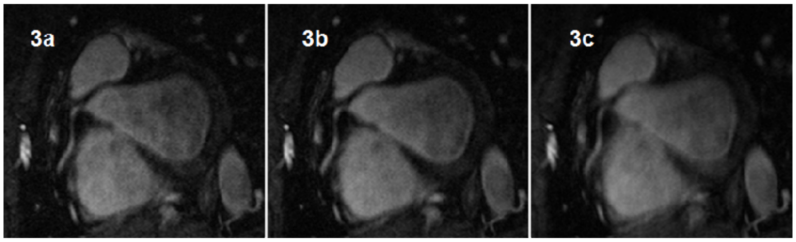

Fig 3: Single slice of a 3D coronary-targeted scan reconstructed using: a) retrospective gating with a 5mm gate, b) motion-adapted average of 3 acquisitions, c) unweighted average of 3 acquisitions. Shown is the root sum of squares of the 5 coil images.

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References: [1] Stuber, Radiology, 1999; [2] Wang, JMRI, 2001; [3] Weigner, MRM, 1997.