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Introduction

The heart moves considerably with the cardiac and respiratory cycles. Typical effects in cardiovascular magnetic resonance (CMR) imaging include misregistration, blurring, ghosting and reduction in signal-to-noise ratio (SNR). In this article we will briefly describe the motion of the heart during the cardiac and respiratory cycles and present ways of compensating, eliminating or minimising the effects of that motion. For a detailed review see Scott et al 2009.

Motion of the heart with the cardiac cycle

Studies using tagged CMR methods and phase velocity mapping have quantified the movement of the heart chambers through the cardiac cycle. During ventricular contraction, the basal part of the heart moves substantially while the apex remains relatively stationary. The ventricles contract with a left handed twist (15° between base and apex), with the walls reaching up to 140mm/s.

Cardiac motion of the coronary arteries is well documented. The right coronary artery is more mobile than the left and the proximal motion is less than the distal. Maximum distal right coronary artery displacements are around 13mm left-right, 17mm anterior-posterior and 10mm superior-inferior (SI). Typically, the period when the arteries are stationary the longest (the coronary rest period) lies in early diastole but is highly subject-specific and may lie in systole for subjects with high heart rates.

Respiratory motion of the heart

Motion of the heart during tidal breathing is subject specific and related to both chest wall and diaphragm motion. Typical end-expiratory and inspiratory dwell times are 1s and 0.5s respectively with a period around 4s, diaphragm range 14mm and maximum diaphragm speed 13mm/s. The heart moves approximately linearly with the diaphragm in the SI direction, although the relationship varies substantially between subjects. The motion is also often hysteretic, meaning that the position of the heart may depend on respiratory phase (inspiratory or expiratory) as well as diaphragm location.

Correcting, compensating and eliminating motion

Motion from the cardiac cycle

Although, real-time CMR imaging is possible, acquisitions are limited in both temporal and spatial resolution and SNR. The majority of studies therefore acquire data over a number of cardiac cycles using the R-wave of the electrocardiogram (ECG) to gate or trigger the acquisition. Cine imaging, where data is acquired throughout the cardiac cycle, may be prospectively or retrospectively gated. Prospective techniques usually acquire data only in the first 80-90% of the cardiac cycle, leaving the remaining 10-20% to allow for beat to beat variations in RR-interval. With all cine techniques there is a trade-off between spatial resolution, temporal resolution and frame rate.

When imaging throughout the cardiac cycle, through-plane motion of the heart will result in variations of the anatomy imaged in each frame. Techniques have been implemented which use a pre-scan to evaluate the structure of interest and track its motion in the subsequent acquisition. Such methods have been used to improve phase velocity mapping of the aortic and mitral valves and obtain high resolution 3D images of the aortic valve. Similarly, the accuracy of measuring the low flow rates in the coronary arteries using phase velocity mapping has been improved by subtracting the velocity of a region of adjacent myocardium or epicardial fat.

Applications requiring single time point imaging, for example coronary artery imaging, usually rely on imaging during the rest period (see figure 1) and suggestions for the optimum gating delay based on the RR interval exist. Ideally, the onset and duration of the rest period should be determined from a cine acquisition in the plane of interest, enabling longer acquisition windows in subjects with long RR intervals and a resultant increase in imaging efficiency without additional motion related blurring.

Respiratory motion

For many CMR applications, breath-holding remains the most popular approach for suppressing respiratory motion artefacts. End-expiratory breath holds are more reproducible than at end-inspiration and the residual motion of the heart is less. Breath-hold duration may be extended using hyper-ventilation and/or hypnotics.

Alternatively, the acquisition may be divided into multiple breath-holds, which may be guided by feeding back respiratory information to the subject. Breath-holding schemes and, in particular, guided techniques require increased patient co-operation, which may not be possible.

Imaging during free-breathing reduces the need for patient co-operation and removes the constraints on acquisition duration. Most free-breathing studies use respiratory information derived from a “navigator”, which is a one-dimensional image of a column of tissue, usually orientated in the SI direction and positioned on the right hemi-diaphragm. Retrospective respiratory gating uses the diaphragm position to retrospectively select and reconstruct the data which was acquired closest to end-expiration from an oversampled (typically by a factor of 5) data set.

Prospective alternatives rely on rapid processing and feedback of the respiratory information in order to enable the sequence to adapt. The acceptance-rejection algorithm (see figure 2) only reconstructs data acquired when the respiratory position is within a pre-defined window (typically 5mm) around end-expiration. Data acquired outside this window are re-acquired in the next cardiac cycle. The respiratory efficiency (the percentage of the data accepted for reconstruction) is highly subject-specific and may be severely diminished by changes in the respiratory pattern during the acquisition.

A number of techniques have been developed to reduce the effects of residual motion within the acceptance window and, therefore, potentially allow an increase in acceptance window size. k-space ordering techniques do this by modifying the acquisition scheme in real-time according to the respiratory position. The diminishing variance algorithm and motion adaptive gating, eliminate the need for a gating window, gradually improving the image by reducing the spread of respiratory positions at which the data was acquired as time progresses. Another common approach is slice tracking which uses a model relating the motion of the diaphragm to that of the heart to track the respiratory motion of the heart and reduce the residual motion within the gating window. Such techniques require accurate models to be effective. Most commonly, a 1D translational model is used where the SI motion of heart is assumed to be 60% of that of the diaphragm. In reality, a single 1D factor for all subjects is inadequate and subject-specific factors are required that may be estimated from an additional pre-scan.
To account for the deformable nature and hysteretic motion of the heart during respiration, more advanced motion models have been used that incorporate additional parameters describing rotation, stretch and skew. Such models often utilise multiple navigators, for example an additional navigator located on the chest wall or an extra diaphragmatic navigator acquired earlier in the cardiac cycle. Using multiple navigators and an advanced 3D subject-specific model for coronary artery imaging, respiratory efficiencies may be increased to around 80% by using a 10mm gating window with a similar level of residual motion to using basic 1D slice tracking with a fixed model and a 5mm window (around 50% efficient). Model-based techniques are, however, unable to adapt to changes in the breathing pattern as the model is fixed at the beginning of the acquisition.

Rather than use navigators, respiratory information may be derived directly from the anatomy of interest without the use of a model. Motion information may be extracted directly from the imaging data or from additional rapid images acquired with the main imaging segment. These techniques use the motion information to reduce, gate and/or correct acquired data or from additional rapid images acquired with the main imaging segment. These techniques use the motion information to reduce, gate and/or correct for respiratory motion in the final images. The 3D spiral fat navigator technique, for example, acquires 3D low resolution fat selective imaging of the cardiac anatomy, immediately prior to a segment of a high resolution acquisition every cardiac cycle. Beat-to-beat 3D respiratory motion information is derived from the low resolution fat images and used to retrospectively correct the high resolution data. This technique was demonstrated initially in 3D dark blood right coronary artery wall imaging with 100% respiratory efficiency, as shown in figure 3.

In conclusion, cardiovascular magnetic resonance studies can often be adequately completed using ECG gating within a single breath hold. It is important, however, to consider the temporal location and duration of the acquisition window within the cardiac cycle for single time point imaging and the trade-off in frame rate verses overall breath-hold duration for cine imaging. Studies that require high spatial resolution and, therefore, longer acquisitions, often use navigator gating and a variety of techniques, which ideally require a subject-specific motion model exist for improving the efficiency and/or image quality of respiratory gated studies. Non-model based respiratory motion correction techniques, although currently mainly limited to research studies, may present a preferable clinical alternative for the future.

References

FIGURE 1
In-plane right coronary images acquired at (a) 450, (b) 550, (c) 650, (d) 750, (e) 850 and (f) 950ms from the R-wave. Note that the right coronary artery appears sharpest in d (where the arrow highlights the clearest depiction of the branching) which corresponds to the optimal delay time of 735msec as determined in a prescan. Reprinted with permission from Wang et al. Radiology 2001; 218:580-585, copyright Radiological Society of North America.

FIGURE 2
The acceptance rejection algorithm uses a navigator echo acquired before (as shown here) or after the main imaging acquisition (segment) to determine the diaphragm position. If the diaphragm position lies within a pre-defined window around end-expiration, the data acquired in the current cardiac cycle is accepted for reconstruction, otherwise it is re-acquired in the next cardiac cycle.
FIGURE 3
Dark blood cross-sectional right coronary artery wall images acquired with 100% respiratory efficiency and corrected for respiratory motion using three techniques, shown with the corresponding diaphragm trace throughout the acquisition. Images are (a) uncorrected, (b) corrected using a fixed 1D SI model, (c) corrected using a subject-specific 3D translational model and (d) corrected using the beat-to-beat displacements obtained with the 3D spiral fat navigator. In this subject, only beat-to-beat respiratory motion correction is able to adequately correct for the motion. Reprinted with permission from Keegan et al. Journal of Magnetic Resonance Imaging 2007; 26: 624-629, copyright John Wiley & Sons.