Real-time navigator approach to motion problems in coronary MRA

Yi Wang
Department of Radiology, Cornell University, New York, USA

Abstract – This paper is a summary discourse on the real time navigator approach to suppressing motion effects in coronary magnetic resonance angiography. The concept of navigator approach, characteristics of coronary motion, design of navigator echoes for motion measurements, and navigator algorithms for motion effects suppression are reviewed and discussed. At the conclusion, an efficient and effective navigator method is suggested for suppressing motion effects in coronary MRA.

Key words – coronary MRA, navigator, motion

I. Introduction

Motion is the most important factor limiting image quality in many clinical applications of MRI (1), including two recent major developments of MRI – cardiac and neurofunctional MRI. Fast imaging techniques have made these major developments possible, but acquiring sufficient spatial resolution and signal-to-noise ratio for resolving small structures and low signals still require data sampling over many cycles of cardiac and respiratory motion. Technological improvement in imaging gradient power has reached a limit such that scan time cannot be substantially shortened by further increases in gradient speed and strength (2). Effective motion suppression techniques are complimentary with fast imaging methods and are essential in allowing greater realization of the potential of MRI.

This paper focuses on motion reduction in coronary MR angiography (CMRA), one of the most challenging areas for motion suppression. The importance of CMRA is dictated by the fact that cardiovascular disease remains the leading cause of death in the developed world (3). The current standard for evaluating coronary artery disease (CAD) is x-ray angiography, which is expensive, invasive and carries risk (4). Noninvasive imaging of coronary arteries has long been desired to provide a screening and follow up tool for patients with CAD. MR angiography has the potential for noninvasive high resolution 3D imaging of the proximal coronary arteries where most clinically significant stenoses are located (5). MR is the only imaging modality that has the potential of the "one-stop shop" for comprehensively assessing coronary stenoses, ventricular function and myocardial perfusion. CMRA is one of the most important components in cardiac MRI, and a recent NIH Working group identified CMRA as the No.1 special area of emphasis for NIH (6).

MR angiography can be obtained by encoding flow information in both the magnitude and phase of MR signal. Traditional methods include time-of-flight and phase contrast techniques (7,8). Early attempts to image coronary arteries using these traditional methods had limited success. Significant progress in coronary MRA (CMRA) was made when fat suppression was used to improve coronary artery contrast (human coronary arteries are embedded in epicardial fat), cardiac motion was minimized by acquiring data during diastole, and respiratory motion was minimized by completing a 2D acquisition within a breath-hold (9). Initial clinical trials using this 2D breath-hold approach yielded variable accuracy because of limitations in spatial resolution (spacing between sections), SNR, and scan setup inherently associated with a 2D acquisition (10,11). These limitations could be overcome by using a 3D acquisition approach (12), which can provide higher SNR and higher spatial resolution than 2D acquisition (13). The tortuous coronary artery tree requires a 3D display to overcome the obstruction of chamber blood. For these reasons, 3D acquisition has been chosen for CMRA by almost all investigators. The fundamental challenge is that the 3D benefits can be diminished by respiration and cardiac contraction during data acquisition. Motion can generate ghosting and blurring artifacts degrading or corrupting the image (14). Motion reduction techniques are therefore required to obtain a high resolution 3D CMRA.

II. Real-Time Navigator Approach

Coronary motion is caused by respiration and cardiac contraction that vary from patient to patient and are not predictable by any model. In this situation, motion effects may only be reduced by measuring motion prior to data acquisition and adjusting data acquisition accordingly. This is the real-time navigator approach, similar to the missile guidance technology (15).

The concept of navigator based motion reduction was introduced to imaging in the early 1950's for correcting the distorting effects of the Earth's atmosphere in ground-based astronomical imaging. Angular resolution is limited not by the size of the primary mirrors (diffraction effects) of telescopes but by the atmospheric turbulence deforming the image on a millisecond time scale (16). Adaptive optical systems consisting of natural or artificial guide stars, wavefront sensors and real-time phase delay corrections have significantly improved image resolution (17). This navigator motion reduction idea has also been very successfully applied in the latest camcorder technology (18,19). Image blurring due to camera shake is a limitation when shooting in high speed and/or high wind conditions. The navigator approach to this problem is to detect the shake of the camera and immediately adjust a correcting lens to compensate for the change in the light ray path. This navigator approach turns out to be the best method for anti-shake high resolution imaging and is now used in commercial cameras.

Similarly, spatial resolution of MR images of the moving coronary artery tree is limited by physiological motion, not by the capability of the MR scanner in sampling high spatial frequencies. Navigator based motion gating and correction techniques were introduced in MRI in the late 80's to reduce motion effects (20,21). Currently navigator motion correction techniques are widely used to correct undesired motion effects in diffusion imaging, fMRI, body MRA and spectroscopy. The initial results from us and others vindicate the utility of these navigator methods for reducing motion effects in CMRA (22-26). In this paper, we provide an overview of the major motion issues of navigator CMRA and identify directions for future developments.

III. Coronary Motion

The majority of motion suppression work in CMRA is focused on reducing respiratory motion effects, assuming the cardiac motion effects can be minimized using a short acquisition window in mid-diastole under the guidance of electrocardiogram (ECG). However, it is known that ECG bears no quantitative correlation to the actual motion of coronary arteries. There can be substantial residual cardiac motion in the ECG triggered CMRA, which is a major cause of degradation in image quality. We shall discuss respiration first, cardiac motion second, and then the total motion of coronary arteries.

Respiration. The heart is positioned superior to the diaphragm, which acts as a piston pushing the heart in the superior-inferior (SI) direction. Respiration waveform varies with a 2-4 sec cycle on a 100 msec time scale. The dominant component of coronary motion due to respiration is a linear translation along the SI direction. There is translation along anterior-posterior (AP) and right-left (RL) directions, and dilation along the SI direction because the coronary roots are displaced less than the distal arteries at the bottom of the heart. However, the magnitudes of these motion components are much smaller than the SI translation (27). The coronary motion due to respiration is approximately correlated to the SI motion of the diaphragm, though there may be hysteresis during the respiration cycle (28). These characteristics imply that the respiratory component of coronary motion can be approximately but not exactly monitored at the diaphragm by measuring the diaphragm's SI position.

Cardiac motion. The coronary motion due to cardiac contraction and rotation (referred here as CARDIAC MOTION) varies with a 1 sec cycle on a 10 msec (or less) time scale. Though ECG is typically used to trigger CMRA acquisition, ECG is not a measure of coronary motion. Cardiac motion can be measured quantitatively using invasive cine x-ray angiography method. In general the cardiac motion waveform has good periodicity. Several properties crucial to CMRA data acquisition have been identified from x-ray angiography motion measurement (29). 1) Rest period or the period of minimal cardiac motion such as motion < 1mm along SI, AP and RL axes. This rest period varies substantially from patient to patient, and depends on the length of the cardiac cycle: the rest period increases with the RR interval in general; it is not uniquely determined by the RR interval. At slow heart rates, the left coronary artery has a substantially longer rest period than the right coronary artery. 2) Velocity around the rest period. Movement immediately before and after the rest period is also important to CMRA acquisition. Velocities can be measured over a 100 msec period immediately preceding and following the rest period: The velocities after the rest period are significantly larger than the velocities before the rest period, and the velocity of the right coronary artery is larger than that for the left coronary artery. This implies that, if an acquisition window is longer than the rest period, it should extend into the time interval proceeding the rest period. 3) Reproducibility of coronary location at the rest period. The spatial locations of the rest-period coronary arteries in adjacent heartbeats can be compared on cine x-ray angiograms to identify reproducibility of coronary location among different heartbeats. The changes in coronary artery positions are less than 0.5 mm, indicating that the heart returns to the same location from heartbeat to heartbeat. This result is consistent with the fact that the heart is normally confined tightly within the pericardial sac. When there is no respiratory motion in the thoracic trunk and no change in cardiac output, the heart should return to the same location from heartbeat to heartbeat.

The cardiac motion can be decomposed into two compartments, global motion (translation, rotation about the long axis and dilation/contraction at the center of the heart) and local deformation that is not accounted for in the global model, including bulging during contraction and twisting caused by non-uniform rotation. A very useful and interesting finding is that, well known in the cardiac wall motion modeling community, most (~91%) of the 3D cardiac motion of coronary bifurcations can be represented in a moving spherical coordinate system (30). That is, as a good approximation, the cardiac motion of the coronary arteries can also be decomposed into linear translation, rotation and dilation/compression. We will demonstrate that the parameters of translation, rotation and dilation can be measured and corrected for using volumetric orbital navigator techniques.

TOTAL GLOBAL MOTION OF CORONARY ARTERY. Here we consider detection of the complete global components of the coronary motion due to respiration and cardiac contraction. The discussion in the above three paragraphs leads to the following mathematical expression for the total global motion of coronary arteries. Let **x** be the position vector $(x, y, z)^T$, and **D** the displacement vector $(D_x, D_y, D_z)^T$. Then the respiratory motion component can be expressed in a matrix form:

$$\mathbf{x}' = C_r(\mathbf{x} - \mathbf{D}), \quad [1]$$

where C_r is a diagonal matrix characterizing compressing/dilation. Cardiac motion can be expressed conveniently in a coordinate system XYZ, with Z the long axis of the heart and XZ in the septum plane. The transformation from the xyz coordinate system to the XYZ coordinate system consists of 1) rotating about the x-axis until the z-axis becomes the Z-axis and 2) rotating about the Z-axis until the x-axis gets to the septum (XZ) plane (both rotating angles can be easily measured from scout scans of the heart). The Jacobian associated with this transformation (J) is the product of these two rotations and can be obtained from a scout scan. The rotation and contraction associated with cardiac motion, adding the respiratory component, is composed of transforming from xyz to XYZ, contraction / dilation (C_c), rotation (R_c), and transforming from XYZ back to xyz:

$$\mathbf{x}'' = J^{-1}R_cC_cJ\mathbf{x}' = J^{-1}R_cC_cJC_r(\mathbf{x} - \mathbf{D}) \equiv A(\mathbf{x} - \mathbf{D}) \quad [2]$$

IV. NAVIGATOR ECHOES FOR MEASURING CORONARY MOTION

The physics of magnetic resonance imaging provides a great capacity that is unparalleled by any other imaging modality for designing methods to excite and sample signals of desired spatial location and chemical characteristics (31,32). In the following we describe various designs of navigator echoes used to measure motion in MRI.

PENCIL BEAM NAVIGATOR ECHO. Until recently motion work in CMRA has been based on monitoring respiration at the diaphragm using the pencil beam navigator (22-26,33). A 2D RF excitation pulse that excites selectively a circular region on one plane but excites uniformly along the axis perpendicular to the plane can be used to acquire a longitudinal cylinder of tissue through the diaphragm dome. Such a pencil-beam navigator echo can be flexibly positioned away from the heart, not affecting the cardiac magnetization. The diaphragm position can be extracted from the navigator profile using an edge detection algorithm. The pencil-beam navigator echo provides easy and good detection of the change in the SI position of the diaphragm, but the AP oriented motion of the chest and upper abdominal wall is not measured. One fundamental limitation of the pencil beam navigator is that the SI motion of the diaphragm measured by the pencil beam navigator is not identical to the SI respiratory motion of the heart. Pencil beam may be positioned directly to monitor cardiac motion activities, but it is difficult to extract motion parameters of coronary motion from a pencil beam profile (34).

ORBITAL NAVIGATOR ECHO. Note that the global motion of coronary arteries can be characterized by a few parameters (~ 10, Eq.2), and that many points (~ 200) are sampled in an echo in MRI. So it is possible to solve all global motion parameters from a single navigator echo by designing k-space sampling trajectories that sensitize all motion components. This leads to the development of orbital navigator echo. First we describe 2D orbital navigator echo that measures rotation and translation simultaneously (35). It describes a circle in 2D k-space and permits simultaneous measurement of in-plane rotation and translation. An object f(**x**) after in-plane motion is f'(**x**) = f(R(**x**-**D**)), where R is the orthogonal rotation matrix, **D** is the translation vector. The corresponding representation in the Fourier space is

$$F'(\mathbf{k}) = e^{i\mathbf{k}\cdot\mathbf{D}} \bullet F(R\mathbf{k}). \quad [3]$$

Based on Eq.3, rotation can be determined from the shift in the magnitude profile of the orbital echo with respect to a reference orbital echo using a least squares algorithm. Then displacements can be calculated from the phase difference ($\Delta\phi(\theta)$) between the current echo and a rotated reference echo: (Spiral trajectory has similar but not as simple property for displacement determination (36).)

$$(D_x, D_y) = \frac{1}{\pi k_\rho}\int_0^{2\pi} \Delta\phi(\theta)(\cos\theta, \sin\theta)d\theta. \quad [4]$$

Of course the coronary artery tree is a 3D structure, and accordingly a 3D orbital navigator echo is needed. Fundamentally the design of k-space trajectory for navigator echo is to sensitize sampled signal to motion parameters. The general k-space expression of the motion effects $f_m(\mathbf{x}) = f(A(\mathbf{x}-\mathbf{D}))$ is:

$$F_m(\mathbf{k}) = e^{i\mathbf{k}\cdot\mathbf{D}}F((A^{-1})^T\mathbf{k}). \quad [5]$$

The six motion parameters in matrix A (the rotation angle in R_c, two scaling factors in C_c, and three scaling factors in C_r) can be determined by the least squares minimization, $\min\{\sum_\mathbf{k}(|F_m(A^T\mathbf{k})|-|F(\mathbf{k})|)^2\}$. This requires sampling a k-space volume where $A^T\mathbf{k}$ might be located around **k**, and a search for the minimal by resampling data. Therefore, the k-space trajectory is much more complex than the circle used in the above 2D case, in order to solve different motion parameters. Under certain situations, trajectories may be simplified. For example, a trajectory consisting of 3 axes can be used to simultaneously detect 3D translation and dilation (37).

A major challenge to coronary motion measurement using volumetric orbital navigator echo is that excited signal should come from coronary arteries, not from the chamber blood pool. Otherwise, the detected signal represents motion of the chamber blood, which is not correlated to the motion of the coronary arteries. Selective excitation of coronary blood is very difficult if not impossible. An ingenious solution is to excite the epicardial fat, whose motion is directly correlated to the motion of coronary arteries, as human coronary arteries are surrounded by epicardial fat. Preliminary data demonstrate that a spatial-spectral selective pulse, with spatial saturation pulses suppressing chest wall, can be used to excite fat from the heart volume (37).

V. NAVIGATOR ALGORITHM

In the real time navigator approach, navigator echoes are acquired immediately prior to image echo acquisition. Both the acquisition and processing of navigator echo should be completed within ~ 10 msec, so that the motion contained in the image echo is approximately the same as that detected by the navigator echo. The information derived from the navigator echo is used to control the acquisition of image echo through an algorithm such as correction, view ordering and gating. Here we illustrate several navigator methods, which can be used towards a comprehensive, efficient and effective navigator algorithm.

CORRECTING FOR ALL GLOBAL COMPONENTS OF MOTION SIMULTANEOUSLY IN REAL TIME. Once the global motion is known, its complex effects on MR signal in Eq.5 can be simultaneously corrected by adjusting the gradients and RF. The gradient adjustment according to the following k-space vector:

$$\mathbf{k'} = A^T\mathbf{k} = C_r J^{-1} C_c R_c^{-1} J\ \mathbf{k}, \qquad [6]$$

which is accomplished on our scanner by setting the "rotation matrix" to A^T prior to playing out the gradients for each echo, corrects for the global rotation and contraction associated with cardiac motion and the dilation associated with the respiration. The motion phase term in Eq.5 can be corrected by adjusting of RF excitation and reception (38). Motions not accounted for in the global motion, such location deformations including those caused by local ischemia, cannot be corrected for but can be reduced by view ordering and gating.

VIEW ORDERING. Local deformations of the coronary arteries due to cardiac contraction and respiration are not measured and corrected for. In general, the motion of coronary arteries may be decomposed as a Taylor series, with the 1st order terms representing global motion measured by navigator echoes, and the 2nd and higher order terms representing local deformations. The local deformations can be reduced through view ordering, which is the focus of this paragraph, and if the ranges of the 1st order terms are reduced with gating, which is the subject of the next paragraph. View ordering can reduce both blurring and ghosting as demonstrated by us and others (39-41). Though the local deformations are very difficult to measure (hence difficult to correct), their magnitudes increase with the magnitudes of the 1st order terms. The measurements of the 1st order motion terms (global motion) can be used as qualitative indicators of local motion in order to design view orders for the minimization of artifacts due to local deformations. A view order of minimal motion may have minimal motion amplitude near the center of k-space, and smooth motion distribution in k-space, because MRI signal is heavily concentrated in k-space center and abrupt changes in k-space lead to ringing and ghosting artifacts. An optimal view order may be identified experimentally. View ordering can minimize motion effects, but it cannot eliminate them.

GATING. Gating is simply to limit the range of residual motion in the image data (22,42), i.e., the final reconstructed image uses data acquired with motion position within a certain tolerance range or gating window, while all other data acquired outside the gating window are not used. A clever way to select the gating window is to gradually reduce it as scan continues by replacing data acquired at positions far away from the mean position. This is called DVA - diminishing variance algorithm that allows the choice of optimal gating window at a given scan time (43).

A fundamental limitation in DVA is that the residual motion is randomly distributed within the gating window. Such residual motion effects can be minimized further by smoothly distributing motion using view ordering. This method combining gating and view ordering is called HOPE - hybrid ordered phase encoding in the case of motion waveform with fixed histogram (41). A generalized version robust against shifting histogram is PAWS - phase ordering with automatic window selection (44). Comparison of PAWS/HOPE with DVA demonstrates that the incorporation of view ordering substantially reduces residual motion effects (44).

The fundamental limitation of gating is that the effectiveness in motion reduction is achieved at the cost of scan efficiency. In order to minimize motion artifacts, the gating window has to be small. Data acquired at other motion positions outside the gating window, which take the majority of the time, are not used in the final image reconstruction. This waste of time can be reduced and almost eliminated using the following approach. Different image volumes can be acquired at different motion positions, thus allowing more data to be used in the final image reconstruction that generates multiple image volumes. This is called MOSAIC - motion organized simultaneous acquisition with interactive control (45). The MOSAIC approach is simple and powerful: the scan efficiency is greatly improved while the effectiveness of motion effects suppression is preserved.

VI. Conclusions

In the paper, we have summarized the real-time navigator approach to motion problems in coronary MRA, which can be applicable to general MRI. Questions fundamental to the real-time navigator approach are: 1) How accurate can we measure coronary motion? 2) How effectively and efficiently can we suppress motion effects? Recent new developments point out very encouraging answers to these two fundamental questions. The volumetric orbital navigator echo allows fast and accurate detection of coronary motion, and the MOSAIC approach allows efficient and effective motion suppression. The combination of orbital navigator echo and the MOSAIC algorithm may lead to an efficient and effective method for suppressing motion effects in coronary MRA.

VII. References

1. Korin HW, Ehman RL. Motion artifact suppression techniques. In: Magnetic resonance imaging of the body, Ed. Higgins CB, Hricak H, Helms CA. 2nd Edition, New York, Raven Press, pp217-232, 1992.
2. Reeder SB. McVeigh ER. The effect of high performance gradients on fast gradient echo imaging. *Magnetic Resonance in Medicine. 32(5):612-21, 1994*
3. American Heart Association. Heart and stroke facts: statistics. Dallas, Texas. p8, 1993.
4. Johnson LW, Lozner EC, Johnson S, et al. Coronary arteryography 1984-1987: a report of the Registry of the Society for Cardiac Angiography and Interventions. I. Results and complicatoins. Cathet Cardiacvasc Diagn. 17:5-10, 1989.
5. Vieweg WV. Alpert JS. Johnson AD. Dennish GW. Nelson DP. Warren SE. Hagan AD. Distribution and severity of coronary artery disease in 500 patients with angina pectoris. Catheterization & Cardiovascular Diagnosis. 5(4):319-30, 1979
6. Budinger TF, Berson A, McVeigh ER, Pettigrew RI, Pohost GM, Watson JT, Wickline SA. Cardiac MR imaging: report of a Working Group sponsored by the National Heart, Lung, and Blood Institute. Radiology 208:573-576, 1998.
7. Potchen, E.M. Haacke, J.E. Siebert, A. Gottschalk, “Magnetic resonance angiography: concepts & applications”, Mosby-Year Book Inc., St. Louis, 1993.
8. Anderson, R.R. Edelman, P.A. Turski, “Clinical magnetic resonance angiography”, Raven Press, New York, 1993
9. Edelman RR, Manning WJ, et al, Coronary arteries: breath-hold MR angiography. Radiology 181:641-643, 1991.
10. Manning WJ, Li W, Edelman RR, A preliminary report comparing MR coronary angiography with conventional angiography, N Engl J Med, 328:828-832, 1993.
11. Duerinckx AJ, Urman MK, 2D coronary MR angiography: analysis of initial clinical results, Radiology 193:731-738, 1994
12. Li D, Paschal CB, et al, Coronary arteries: 3D MR imaging with FS and MTC, Radiology 187:401-406, 1993.
13. Parker DL, Gullberg GT, Signal-to-noise efficiency in magnetic resonance imaging, Med. Phys. 17:250-257, 1990.
14. Wang Y, Grist TM, et al, Respiratory motion blurring in 3D coronary imaging, Magn Reson Med 33:541-548, 1995.
15. McCraw-Hill Encyclopedia of Science & Technology, 8th Edition, Vol. 11, pp313-317, 1997.
16. Babcock HW, The possibility of compensating astronomical seeing, Publ. Astron. Soc. Pac. 65, 229,1953.
17. Thompson LA, Adaptive optics in astronomy, Physics Today, 27(12):24-31,1994.
18. Shake-free video, Popular Science, p48, September 1998.
19. Kitajima. Camera with a function of preventing a hand moving blur. United States Patent 5,109,249, Apr. 28, 1992
20. Hinks RS, Monitored echo gating (mega) for the reduction of motion artifacts, Proc. 6th SMRI, p.48, 1988.
21. Ehman RL, Felmlee JP, Adaptive technique for high-definition MRI of moving structures, Radiology 173:255-263,1989.
22. Wang Y, Rossman PJ, et al, Navigator-based real-time respiratory gating and triggering for reduction of respiration effects in three-dimensional coronary MR imaging, Radiology 198:55-60, 1996.
23. Li D. Kaushikkar S. Haacke EM. Woodard PK. Dhawale PJ. Kroeker RM. Laub G. Kuginuki Y. Gutierrez FR. Coronary arteries: three-dimensional MR imaging with retrospective respiratory gating. Radiology. 201(3):857-63, 1996
24. Jhooti P, Keegan J, Gatehouse PD, Collins S, Rowe A, Taylor AM, Firmin DN, 3D coronary artery imaging with phase reordering for improved scan efficiency, Magn. Reson. Med. 41:555-562, 1999.
25. Stuber M, Botnar RM, Danias PG, Kissinger KV, Manning WJ. Submillimeter three-dimensional coronary MR angiography with real-time navigator correction: comparison of navigator locations. Radiology 1999 Aug;212(2):579-87
26. Thedens DR, Irarrazaval P, Sachs TS, Meyer CH, Nishimura DG. Fast magnetic resonance coronary angiography with a three-dimensional stack of spirals trajectory. Magn Reson Med. 1999 Jun;41(6):1170-9.
27. Wang Y, Riederer SJ, Ehman RL, Respiratory motion of the heart: kinematics and the implications for the spatial resolution in coronary imaging, *Magnetic Resonance in Medicine*, 33, 713-719, 1995.
28. Nehrke K, Bornert P. Study of the respiratory motion of the heart using multiple navigator pulses. ISMRM, 404, 200.
29. Wang Y, Vidan E, Bergman GW. Cardiac motion of coronary arteries: Variability in the rest period and

implication for coronary MR angiography. *Radiology*, 213:751-758, 1999.
30. Potel MJ, MacKay SA, Rubin JM, Aisen AM, Sayre RE. Three-dimensional left ventricular wall motion in man. Coordinate systems for representing wall movement direction. Invest Radiol. 1984;19(6):499-509.
31. Pauly J, Nishimura D, Macovski A. A k-space analysis of small-tip-angle excitation. J. Magn. Reson. 81, 43-56 (1989)
32. Meyer CH. Pauly JM. Macovski A. Nishimura DG. Simultaneous spatial and spectral selective excitation. *Magnetic Resonance in Medicine. 15(2):287-304, 1990*
33. Liu Y, Riederer SJ, et al, A monitoring, feedback, and triggering system for reproducible breath-hold MR imaging, Magn Reson Med 30:507-511, 1993.
34. Wang Y, Watts R, Mitchell IR, Nguyen TD, Bezanson JW, Bergman GW, Prince MR. Coronary MR Angiography: Selection of acquisition window of minimal cardiac motion with electrocardiography-triggered navigator cardiac motion prescanning – initial results. Radiology, 218: 580-585, 2001.
35. Fu Z, Wang Y, et al, Orbital navigator echoes for motion measurements in MRI, Magn Reson Med 34:746-753, 1995.
36. Khadem R, Glover GH. Self navigation for motion in spiral scanning. Proc. ISMRM 1994, p.346.
37. Nguyen TD, Prince MR, Wang Y. A Novel Navigator Technique for Fast and Direct Detection of 3D Displacement of the Coronary Arteries. p173, ISMRM 2001.
38. Grimm RC, Rossman PJ, et al, Real-time adaptive motion correction using navigator echoes, Proc. 3rd SMR, p.741, 1995.
39. Wang Yi, Winchester PA, Yu L, Watts R, Ding G, Lee HM, G. Bergman. Breath-hold three-dimensional contrast-enhanced coronary MR angiography: Motion-matched k-space sampling for reducing cardiac motion effects. *Radiology*, 215:600-607, 2000.
40. Weiger M, Bornert P, Proksa R, Schaffter T, Haase A. Motion-adapted gating based on k-space weighting for reduction of respiratory motion artifacts. Magn Reson Med. 1997 Aug;38(2):322-33.
41. Jhooti P. Wiesmann F. Taylor AM. Gatehouse PD. Yang GZ. Keegan J. Pennell DJ. Firmin DN. Hybrid ordered phase encoding (HOPE): an improved approach for respiratory artifact reduction. *Journal of Magnetic Resonance Imaging. 8(4):968-80, 1998*
42. Sachs TS, Meyer GH, et al, Real-time motion detection in spiral MRI using navigators. Magn Reson Med 32:639-645, 1994.
43. Sachs TS, Meyer CH, et al, The diminishing variance algorithm for real-time reduction of motion artifacts in MRI, Magn Reson Med 34:412-422,1995.
44. Jhoot P, Gatehouse PD, Keegan J, Bunce NH, Talor AM, Firmin DN. Phase ordering with automatic window selection (PAWS): a novel motion-resistant technique for 3D coronary imaging. Magn Reson Med 43:470-480, 2000.
45. Kolmogorov VN, Wang Y, Watts R, Prince MR, Zabih R. An efficient real-time navigator algorithm: motion organized simultaneous acquisition with interactive control (MOSAIC), MIAR 01, Hongkong, 2001.