Journal of Cardiovascular Magnetic Resonance®, 3(3), 183–193 (2001)

Navigator Echoes in Cardiac Magnetic Resonance

David Firmin and Jenny Keegan

Imperial College National Heart & Lung Institute & Royal Brompton and Harefield NHS Trust, London, United Kingdom

ABSTRACT

Navigator echoes are frequently used in cardiac magnetic resonance to monitor respiratory motion and have proved particularly useful in coronary artery imaging techniques where they allow the acquisition of data over multiple reproducible breathholds and during free breathing. The large number of variables involved in their use, however, is such that an optimal method of application may yet have to be developed. In this review article, we examine the issues relating to their implementation and describe the ways in which the navigator information obtained may be used.

Key Words: *Cardiac MR; Navigators; Respiratory motion*

INTRODUCTION

In recent years there has been considerable development in cardiac magnetic resonance (MR). The complex motion of the heart, however, makes it a difficult organ to image and often renders existing methods unreliable. Although cardiac triggering addresses the pumping motion throughout the cardiac cycle, the heart's position from one beat to the next can vary considerably due to respiration. The detrimental effects of breathing on the quality of cardiac studies were first well illustrated by Atkinson and Edelman in 1991 (1) when they showed improved detail in breathhold segmented k-space gradient echo images compared with conventional nonbreathhold images. Although breathhold imaging produces images that are free of respiratory motion artifact, it is not without problems. Specifically, the breathhold position may vary from one breathhold scan to the next, giving rise to misregistration effects, and may also vary during the breathhold period itself (2), resulting in image blurring, respiratory artifact, and the need for repeat acquisitions. In addition, the need to acquire all the data within the duration of a comfortable breathhold period places constraints on the imaging sequence parameters, which limit the signal-to-noise ratio and spatial and temporal resolution achievable.

The idea of navigator echoes for measuring the displacement of a moving structure was first introduced by

Address correspondence and reprint requests to David N. Firmin.

Ehman and Felmlee in 1989 (3). The navigator echo is the signal from a column of material oriented parallel to the direction of the motion to be monitored. After Fourier transformation of this signal, a well-defined edge of the moving structure can be used to measure its position at that time.

In cardiac MR, navigator echoes are usually positioned through the diaphragm and are used to track respiratory motion. The information obtained can be used in a number of ways to produce images with limited respiratory motion artifact and blur, albeit at the expense of prolonged acquisition times and reduced scan efficiencies. In this review we discuss their implementation and application to help improve the definition of cardiac structures on MR images.

Although there is considerable knowledge regarding the physiology of respiration, there is relatively little understanding of the relationship between respiration and the related motion of the heart (4,5). We know that the heart is held in the pericardial sack and is attached to the great arteries and veins and that its inferior surface sits on the moving diaphragm. The three-dimensional motion and deformation of the heart with respiration, however, is likely to vary considerably depending on many factors, including its size and orientation and the breathing characteristics of the person. A better understanding of this motion is likely to improve the methods of respiratory correction for cardiac MR in the future.

It is important to note at this stage the many variables in the application and use of navigator echoes; although there have been some attempts to study these, as is described below, it is unlikely that we are near to optimizing their application at present. The factors discussed include implementation issues such as column positioning, requirement for multiple columns, timing and methods of column selection and edge detection, and factors relating to the use of the navigator information such as slice/slab following, adaptive motion correction, and the requirement for correction factors.

NAVIGATOR ECHO IMPLEMENTATION

Method of Column Selection

Two methods have been used to select a column of signal for the navigator echo. The spin echo technique (3) uses a spin echo sequence with the planes selected by the 90- and 180-degree radiofrequency pulses being either orthogonal or at an angle such that the spin echo signal is formed from a column of rectangular or parallelogram cross-section (Fig. 1a). The advantage of this approach is that it is particularly robust and produces an extremely well-defined column. It cannot, however, be repeated rapidly, and care has to be taken that saturated or other affected tissue does not impinge on the region of interest (Fig. 1b).

The alternative approach is to use a selective two-dimensional radiofrequency pulse to excite the signal in a column of approximately circular cross-section (6). Although this is much more sensitive to factors such as shimming errors, which can potentially cause blurring and distortion of the column, it has the advantages that, with a reduced flip angle, it can be repeated more rapidly and the navigator artifact is less extensive. Both methods are used routinely for research studies on coronary imaging, without any reported problems.

Correction Factors

In cardiac MR, navigator echoes are most frequently used to measure the position of the diaphragm. However, only the inferior portion of the heart that sits on the diaphragm will move this much, whereas superiorly the relative motion will be reduced. This was first studied by Wang et al. (7), who measured the displacements of the right coronary artery root, the left anterior descending artery, and the superior and inferior margins of the heart relative to that of the diaphragm in 10 healthy subjects. For the right coronary artery origin, the mean (± SD) relative displacement (or correction factor) was 0.57 ± 0.26. McConnell et al. (8) and Danias et al. (9) were the first to use this correction factor to adjust the position of the imaging slice during breathhold and respiratory gated acquisitions, respectively, and showed improved image quality. This technique, called real-time prospective slice-following, is now used routinely for both two-dimensional and three-dimensional methods of acquisition. The relatively high SD of the correction factor noted above reflects considerably intersubject variation. In 1999 Taylor et al. (10) measured the correction factors for proximal right and left coronary arteries for individual subjects using a simple two-point technique. This entailed measuring the displacement of the coronary artery of interest between rapidly acquired inspiratory and expiratory breathhold coronal scans and dividing by the displacement of the right hemidiaphragm as measured by interleaved navigator echoes. This two-point technique enabled a rapid and practical assessment of the subject-specific correction factor and was shown to agree well with that obtained from a seven-point technique where the correction factor was defined as the gradient of the plot of coronary artery versus diaphragm displacement over seven breathhold acquisitions. The authors show

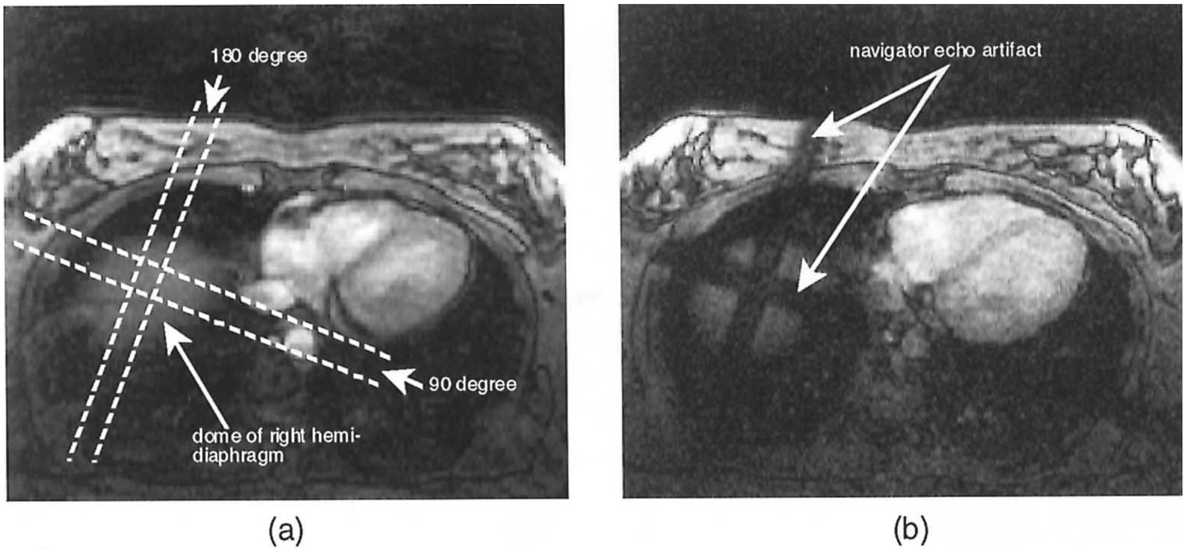


Figure 1. (a) Positioning of slice-selective planes such that their intersection is over the dome of the right hemidiaphragm. (b) The resulting navigator artifact.

that by using an accurate correction factor, a wider acceptance window of diaphragm positions could be used without the image degradation that would otherwise result. Figure 2 shows the relationship between the motion of the right hemidiaphragm and the proximal left coronary artery measured in one subject using the seven-point technique, where the slope of the graph gives the correction factor. Figure 3 shows two examples of subjects with very different correction factors, illustrating how a wider acceptance window can be used, thus improving image efficiency. The need for a subject-specific correction factor has further been confirmed in three-dimensional coronary angiography where its use was found to yield optimal image quality (11).

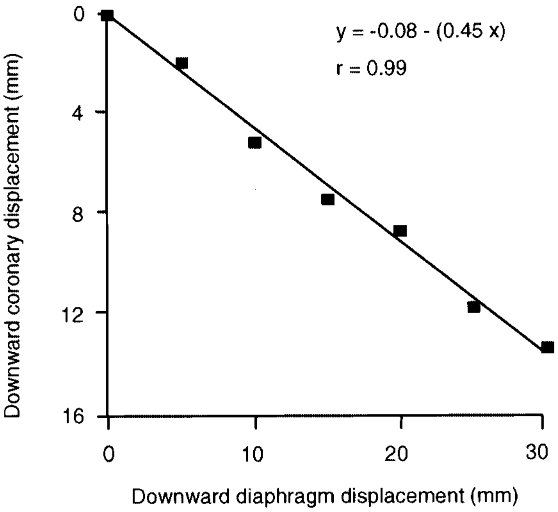


Figure 2. Plot of superior/inferior proximal left coronary artery displacement against superior/inferior diaphragm displacement for a single subject. The gradient of the linear regression line is the subject-specific correction factor. (From Ref. 10, with permission.)

An additional or alternative approach to the real-time slice-following described above is to use a postprocessing adaptive motion correction technique (12,13) to retrospectively correct an image for movement occurring during the data acquisition, the movement being measured by navigator echoes interleaved with the imaging sequence. This technique, which can be used to correct a two-dimensional acquisition for in-plane displacement or a three-dimensional acquisition for displacement in all three directions, may not initially appear to be a particularly beneficial approach, but it has the advantages of allowing the correction factor to be optimized for each individual patient and provides an alternative option to those centers whose scanners do not have a real-time decision making capability. This approach has been implemented with both segmented k-space gradient echo and interleaved spiral coronary artery acquisitions with promising results (14).

Column Positioning

The degree of diaphragm motion detected by the navigator echo is dependent on the positioning of the naviga-

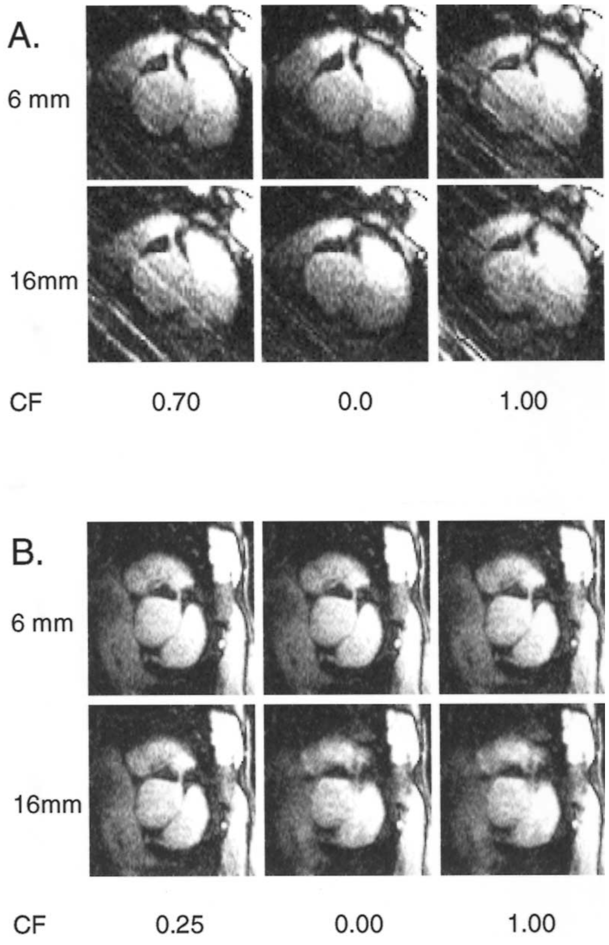


Figure 3. Right coronary artery origin images acquired with navigator acceptance windows of 6 mm and 16 mm in subjects with subject-specific correction factors (CFs) of (A) 0.7 and (B) 0.25. For both subjects, images were also acquired with CFs of 0 and 1. In the absence of slice-following (CF = 0), image quality is reduced as the navigator acceptance window increases from 6 mm to 16 mm. When slice-following with a subject-specific CF is used, however, image quality is maintained. (From Ref. 10, with permission.)

tor column. The dome of the right hemidiaphragm is higher than that of the left, and the two move coherently with respiration but to differing degrees (15). Motion of the diaphragm is also greater posteriorly than anteriorly (anterior and dome excursions being 56% and 79%, respectively, of posterior excursions) and at the level of the dome is greater laterally than medially (16). Despite being less mobile than the posterior and lateral portions of the diaphragm, the dome is generally selected for navigator monitoring because it is perpendicular to the direction of motion over a wide range of motion and consequently results in a sharp edge, easily suited to edge detection techniques.

Alternatively, the heart itself may be selected for navigator placement (17). McConnell et al. (18) investigated the effects of varying the navigator location on the image quality of coronary artery studies. Navigators were positioned through the dome of the right hemidiaphragm, through the posterior portion of the left hemidiaphragm, through the anterior and posterior left ventricular walls, and through the anterior left ventricular wall, as shown in Fig. 4. The results, summarized in Table 1, show no significant differences in the image quality scores obtained with varying navigator location, and although there was a tendency for the anterior left wall navigator scans to be longer in duration, this did not reach statistical significance. A potential advantage of a left ventricular navigator is that the motion of the proximal coronary arteries should match that of the ventricle and the need for a subject-specific correction factor in slice-followed acquisitions, as described in the previous section, should therefore be removed. This has been suggested by Danias et al. (5), who used real-time MR imaging to show large variations in the relationship between craniocaudal coronary artery and diaphragm motion both between and within subjects during free breathing. A recent report (19), however, showed no significant differences in the delineation of proximal coronary arteries in slice-followed acquisitions using left ventricular and right hemidiaphragm navigators (with correction factors fixed at 1.0 and 0.6, respectively). The navigator acceptance windows implemented in this study were small (3 mm and 5 mm, respectively), and differences may become more apparent as the window size is increased to improve scan efficiency. Potential problems when using left ventricular navigators are that the anatomy of the heart is complex and finding a suitable position for the navigator, which does not interfere with the structures being imaged, is difficult. It is hoped that more sophisticated methods of positioning the column will further improve this method of monitoring cardiac motion.

Multiple Column Orientations

A linear relationship has been shown between the superior/inferior and anterior/posterior motions of the heart, with the superior/inferior motion being approximately five times that of the anterior/posterior motion (7). For this reason the real-time slice-following methods first used by McConnell et al. (8) and Danias et al. (9) included a correction for anterior/posterior motion of the heart, assuming it to be equal to 20% of the superior/

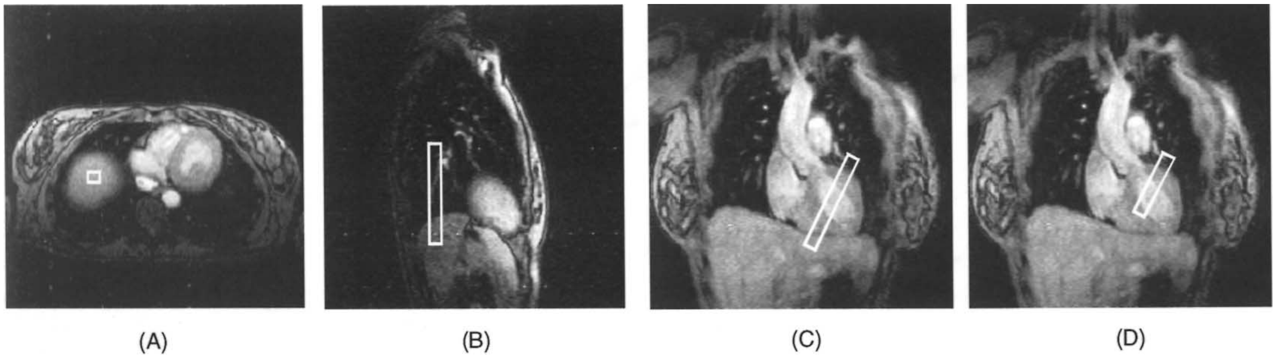


Figure 4. Navigator column locations positioned on transverse, coronal, and sagittal pilot images: (A) through the dome of the right hemidiaphragm, (B) through the posterior left hemidiaphragm, (C) through both anterior and posterior left ventricular walls, and (D) through the anterior left ventricular wall.

inferior motion. Unfortunately, there is not always such a strong relationship between the directions of motion of the heart with respiration. Sachs et al. (20) showed this by using three navigators to measure the inferior/superior, anterior/posterior, and right/left motions of the heart. Figure 5 shows an example from this study illustrating the scatter of superior/inferior, right/left, and anterior/posterior measurements made over a period of approximately 10 min. The group went on to compare the use of one, two, and three navigators for imaging the right coronary artery and showed an improvement when all three directions of motion were measured. Despite this improvement in image quality, however, this has to be offset against the main disadvantage, which is that the scan efficiency is reduced, potentially introducing more problems associated with long-term drift in the breathing pattern.

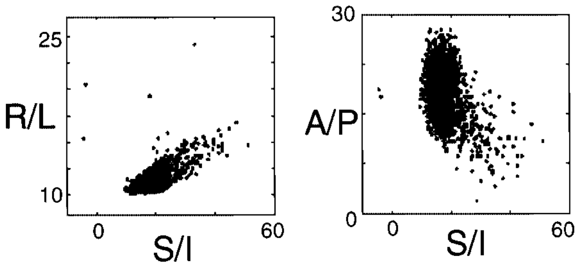


Figure 5. Graphs showing right/left (left) and anterior/posterior (right) navigator echo measurements as a function of superior/inferior navigator echo measurements in a healthy subject. (Data provided by Todd Sachs, Stanford University.)

Table 1

Image Quality Scores (0 = very poor, 4 = excellent), Registration Errors and Total Scan Times for Different Navigator Column Positions During Free-Breathing MR Coronary Angiography

Parameter	Right Diaphragm Navigator	Left Diaphragm Navigator	Left Ventricle Navigator	Anterior Left Ventricle Wall Navigator
Image quality score (0–4)	2.3 ± 0.1	2.3 ± 0.1	2.4 ± 0.1	2.2 ± 0.2
Registration error (mm)				
Craniocaudal	0.5 ± 0.1	0.4 ± 0.1	0.6 ± 0.1	0.4 ± 0.1
Anteroposterior	0.3 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.4 ± 0.1
Total scan time* (sec)	294 ± 28	314 ± 30	342 ± 62	427 ± 111

Values are means + SEM. There were no statistically significant differences between the navigator column locations.
* Total scan time is the time from start to finish for six scans.
From Ref. 18, with permission.

Navigator Timing

Various options for the timing of the navigator relative to the data acquisition window exist and depend to some extent on the computing architecture of the scanner being used and the method of column selection. Figure 6 illustrates the four main alternatives: pre only, pre and post, post only, and navigators repeated regularly throughout the cardiac cycle. For coronary artery imaging in mid-diastole, a simple prenavigator provides the highest scan efficiency when a navigator acceptance window is used, but this may not be reliable if there is a sudden change in breathing between the navigator measurement and the image data acquisition. Similarly, if the data acquisition period is long, as in cine imaging, the respiratory position of the heart may change over the acquisition period and the efficacy of the technique may be decreased for the later cine phases. Pre- and postnavigators overcome this problem but of course also reduce the scan efficiency. In our experience, the use of prenavigators only produces acceptable results for free-breathing studies, whereas multiple breathhold acquisitions certainly require both pre- and postnavigators. An important factor, which depends on the computer hardware and architecture, is the time required after the navigator acquisition before the start of the imaging sequence. Particularly if prenavigators only are being used, the longer this time interval the greater the potential for errors caused by respiratory motion. Also, for electrocardiographic R-wave triggered scans, the implementation of prenavigators has implications for the minimum gating delay at which an image may be acquired, and consequently for imaging early in the cardiac cycle, postnavigators may be preferable.

Cine or multislice imaging can be improved by repeating navigators more frequently through the cardiac cycle. The potential problem with this is that the navigator signal-to-noise ratio could be reduced, and this may affect the accuracy of the navigator edge detection. In addition, as the number of navigators increases, the available time for imaging decreases and the number of phases or slices that can be acquired will be reduced.

Precision of Navigator Measurement

The precision of the navigator echo measurement depends to a large extent on the signal-to-noise ratio and the spatial resolution of the navigator measurement. Commonly, a spatial resolution of 1 mm is used by, for example, having a field of view of 256 mm and sampling 256 points on the navigator read-out. The most important factor affecting signal-to-noise is the coil arrangement. If, for example, a single coil is used for imaging and navigator detection, it has to be big enough to cover both the imaging area of interest and the region of navigator detection. On the other hand, if phased array coils are used, it can be possible to position one coil specifically for navigator detection, possibly over the region of the right diaphragm. Another important factor in the precision of the measurement is the quality of the edge on the navigator trace. To obtain a well-defined edge of the

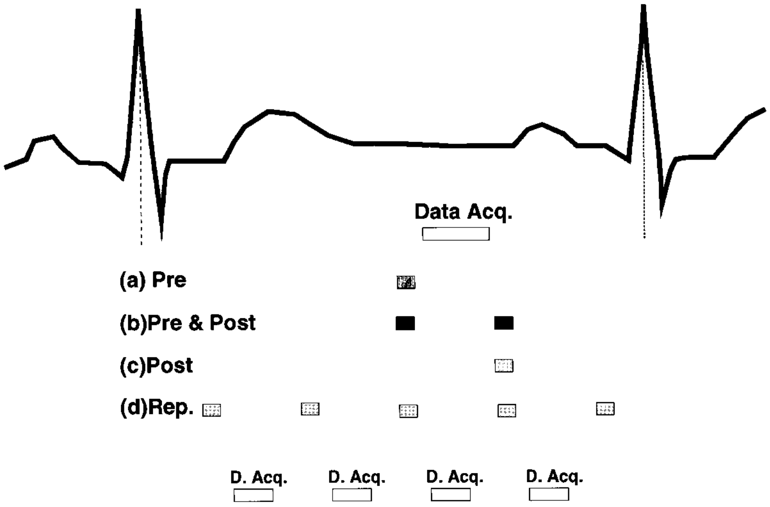


Figure 6. Diagram showing the timings of navigators for pre (a), pre and post (b), post (c), and repeated (d) navigator echo-controlled acquisitions. Typical data aquisition windows are shown for both single and multiple acquisitions.

diaphragm, for example, it is important to have a reasonably small column cross-section and to position it through the dome of the diaphragm, so that the column is perpendicular to the diaphragm edge rather than more posteriorly where motion is greatest. Finally, the diaphragm edge may be detected by edge detection, correlation, or least-squares fit algorithms. For rapid tracking (repetition time <100 msec), the signal-to-noise ratio in the diaphragm trace would be too poor for simple edge detection methods to succeed. Of the remaining two techniques, the least-squares fit method has been shown to be more resistant to the effects of noise and to the diaphragm profile deformation that occurs during respiration than the correlation method and would be the technique of choice (21). However, most navigator techniques acquire only one or two navigators per cardiac cycle, and in such cases signal-to-noise ratios are relatively high and edge detection algorithms generally adequate.

Computer Architecture

Modern MR scanners generally contain three main computers: the host computer, which runs the user interface and allows connection to the image database; the reconstruction computer, which is a dedicated rapid processor for reconstruction of the MR image data; and a scan computer, which allows control and adjustment of parameters associated with the scanning sequence. The architecture of these computers can significantly affect the potential and usefulness of navigator echoes. On many systems, for example, the navigator signal must be reconstructed and processed on the reconstruction computer but the measurement made must be passed through the host to control the parameters on the scan computer. This arrangement inevitably adds a variable and unknown delay dependent on other tasks being performed by the host operating system. To overcome this, either a direct and rapid link is required, allowing transfer of data from the reconstruction to the scan computer or the scan computer itself must be capable of acquiring and reconstructing the navigator data, so that no data transfer is required.

USE OF NAVIGATOR INFORMATION

Two distinct methods of using navigator echoes to reduce problems of respiratory motion in cardiac MR are multiple breathholding with feedback and free breathing. The first of these methods uses the navigator information to provide visual feedback to the subject to allow them to repeatedly hold their breath at the same point (22). The second uses the navigator echo measurement as an input to some form of respiratory gating algorithm while the patient is free breathing. Figure 7 demonstrates actual respiratory trace data in a subject when free breathing and when performing multiple breathholds. In either case, a navigator acceptance window is defined and data acquired with the navigator outside of this window is ignored. The respiratory or scan efficiency is defined as the percent of navigator traces collected that fall within the navigator acceptance window and is a measure of the data rejection rate that in turn determines the overall scan duration.

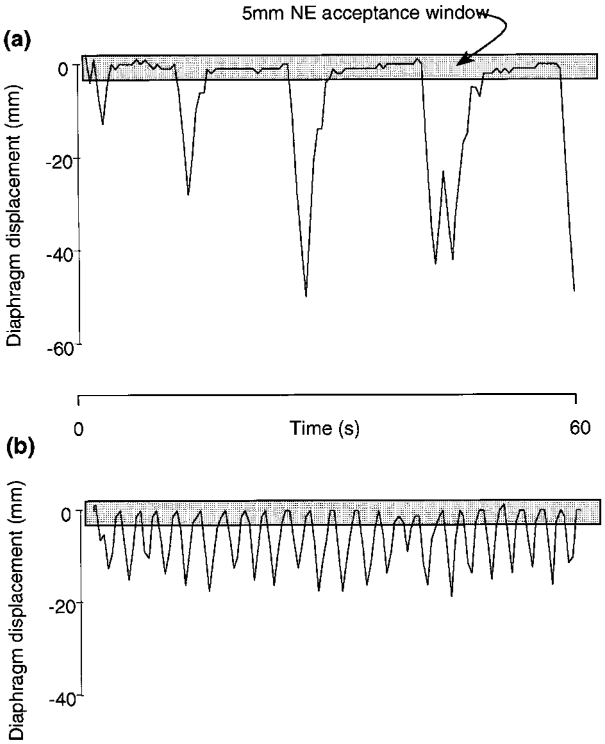


Figure 7. Navigator echo respiratory trace data during (a) multiple breathholding with navigator feedback and (b) free breathing. In each case, the shaded region shows the position of a 5-mm navigator acceptance window. (From Ref. 25, with permission.)

As the navigator acceptance window is reduced, the range of respiratory motion over which data are acquired is reduced, but the rejection rate increases and the scan efficiency falls. A window width of 5 mm is generally chosen as a compromise, which allows the acquisition of good quality images with reasonable scan efficiencies. Figure 8 demonstrates the variability in diaphragm posi-

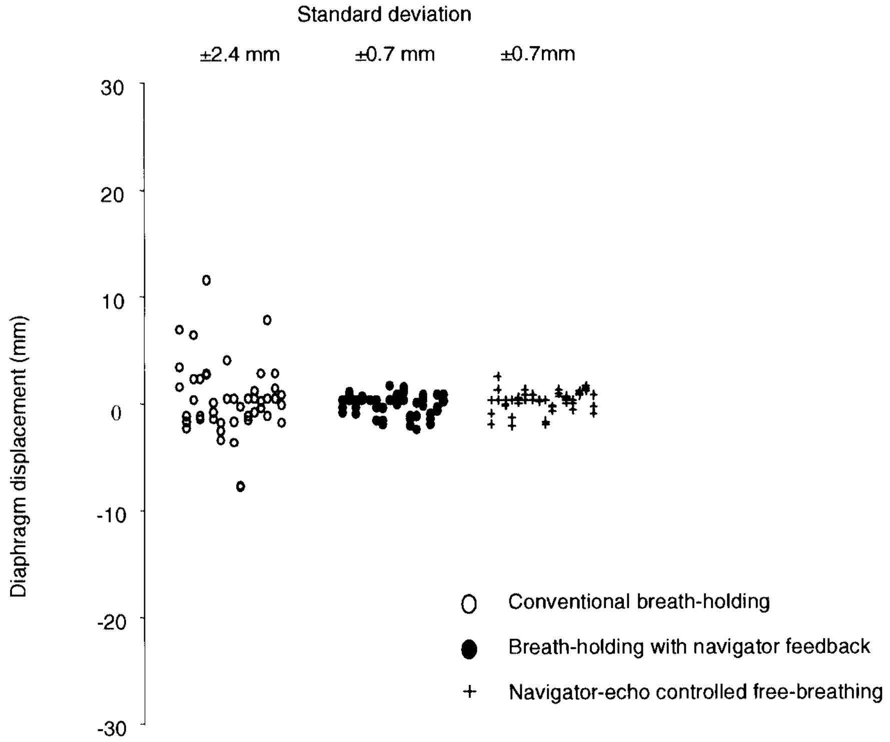


Figure 8. Mean diaphragm displacements in 17 normal subjects for conventional breathholding, for breathholding with navigator feedback, and for navigator-controlled free breathing with a 5-mm navigator acceptance window. (From Ref. 25, with permission.)

tion measured when using the different methods of respiratory control. The navigators allow a longer overall scan time than would be possible for a single breathhold, and this in turn allows for averaging of data to improve the signal-to-noise ratio, increasing the k-space coverage for improved spatial resolution and increased temporal resolution by reducing the number of data segments acquired per cardiac cycle.

Multiple Breathhold Methods

Wang et al. (23) were the first to demonstrate the use of a respiratory feedback monitor to reduce misregistration artifacts in consecutive breathhold segmented k-space gradient echo coronary artery images and to demonstrate improved image quality from averaging scans acquired over multiple breathholds. On informed healthy volunteers, this technique has been shown to produce good results with reasonable efficiency (24). However, a period of training is required, and the process can be problematic, particularly with patients who have difficulty holding their breath (25). This requirement for resting periods and for training results in an extended study time, and in a study of a group of patients with coronary artery disease, there was no significant difference between the examination times achieved when using multiple breathholding and free-breathing techniques, although in normal subjects multiple breathholding was on average 20% faster ($p < 0.05$) (25).

Free-Breathing Methods

Free-breathing methods have the advantage that they require very little cooperation from the subject or patient being scanned and for navigator acceptance windows of 3 mm and 5 mm, the image quality obtained is similar to that achieved with conventional breathholding (9). Although increasing the navigator acceptance window to 7 mm results in a reduction in the imaging time (33% compared with the 3-mm window, 12% compared with the 5-mm window), the image quality obtained is also significantly reduced. Consequently, a 5-mm window is typically used in these acquisitions, although this may be widened without loss of image quality if real-time or postprocessing motion correction techniques are implemented. The acceptance window is normally positioned about the end-expiratory position because this is sustained for longer and with greater stability than the end-

Table 2

Three-dimensional MR Coronary Angiography: Mean Image Quality Scores (1 = excellent, 10 = very poor) and Scan Efficiencies (±SD) for Data Acquired Using Phase Ordering, an Accept/Reject Algorithm (ARA), the Diminishing Variance Algorithm (DVA), and Retrospective Respiratory Gating (RRG) in 15 Subjects

	Phase Ordered	ARA	DVA	RRG
Image quality mean score	4.4	4.7	6.6	6.8
Scan efficiency	72 ± 11.6	48 ± 11.5	72 ± 11.6	20

From Ref. 32, with permission.

inspiratory position (26). The main disadvantage is the potential of respiratory drift, which can cause considerably reduced scan efficiency. Recently, most effort has gone toward improved scan efficiency for use with these gating approaches.

Much of the early work used the method of retrospective respiratory gating (27), which is inherently inefficient. The particular scanner used for these studies was not capable of prospective control, so the only option for respiratory gating was to oversample four or five times and then to retrospectively sort the narrowest respiratory window possible from the acquired data. Hofman et al. (28) showed that by using this approach, the image quality of three-dimensional coronary acquisitions were improved over those acquired with multiple averages. However, the scan efficiency was poor, and although the final image was constructed from the narrowest respiratory window possible for that oversampled acquisition, the range of included respiratory positions was highly dependent on the subject's breathing pattern during the acquisition and may still be unacceptably high.

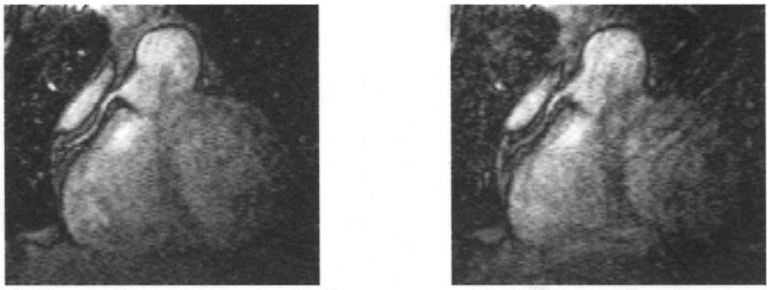
Following the possibility of prospective control, navigators have been used with a simple accept/reject algorithm where data are acquired or not, depending on whether the navigator measurement is within a predefined acceptance window. This approach was initially developed by Sachs et al. (29), and Oshinski et al. (30) were the first investigators to use it to demonstrate high quality coronary images. The problem with this method is that for reasonably high scan quality a narrow acceptance window of 5 mm or less is generally required, which generally results in relatively poor scan efficiency. This is compounded by the fact that many subjects and patients undergo a drift in diaphragm position over time (26), such that the predefined acceptance window becomes less and less suitable as the scan progresses, and as the scan continues, the greater this problem becomes. The diminishing variance algorithm overcomes this problem because it does not use a predefined acceptance window (17). With this method, one complete scan is acquired and the navigator position is saved for each line of data. At the end of the initial scan, the most frequent diaphragm position is determined, and a process of reacquiring lines of data acquired with diaphragm positions offset from this begins. As time progresses the range of diaphragm positions for the complete data set is considerably reduced. For the detailed coronary structures, this should result in considerably less blurring than the accept/reject algorithm method, in which a 5-mm acceptance window is relatively large. As well as the lack of requirement of an acceptance window, this method has the advantage that an image can be reconstructed at any time after the initial data set is complete.

Another alternative to the simple accept/reject algorithm, which can both improve image quality and scan efficiency, is to use a more intelligent ordering of k-space with diaphragm position. Two similar approaches have been suggested, both of which use the fact that the center of k-space appears to be more sensitive to motion than the edges (31). Jhooti et al. (32) developed a phase encode ordered method, which used a dual acceptance window of 5 mm for the center of k-space and 10 mm for the outer regions. This approach enabled a much greater scan efficiency than the other methods while retaining the scan quality (Table 2 and Fig. 9). An alternative method developed by Sinkus and Bornert initially to address general respiratory motion (33) and more recently applied to imaging of the coronary arteries (34) used a tailored acceptance window that progressively increased in size in a defined manner toward the edge of k-space as opposed to attempting to order the phase encode lines and obtained a very similar result.

CONCLUSION

Navigator echoes have been shown to be an important method for defining the position of the heart, enabling improved coronary and other cardiac imaging. Because of the many parameters and variables involved in their use, an optimal method of application may well have yet to be developed. Certainly with future system development there will be minimal cost, in imaging time or other factors, involved in obtaining this positional information, and it would therefore seem worthwhile to collect it. At present, the methods are not totally robust, probably because of their relative lack of sophistication.

One of the major advantages is that navigators allow images to be acquired during free respiration, which takes



(a) Phase ordered (scan eff. = 73%)

(c) DVA (scan eff. = 73%)

(b) ARA (scan eff. = 49%)

(d) RRG (scan eff. = 20%)

Figure 9. A single slice from a three-dimensional data set showing a long section of the right coronary artery. The phase ordered images (a) are of comparable image quality to those acquired with the accept/reject algorithm (ARA) (b) and better than those acquired with both the diminishing variance algorithm (DVA) (c) and retrospective respiratory gating (RRG) (d). The scan efficiency is also significantly higher for phase ordering than both ARA and RRG. (From Ref. 32, with permission.)

away the requirement of patient cooperation. They also allow longer acquisition times, enabling higher spatial and temporal resolution and increasing the potential of more sophisticated techniques such as detailed flow imaging. A balance has to be met, however, and the imaging time should not be increased so much that increased respiratory drift cancels any potential benefit. With development enabling more general measures of cardiac position and rotation of the heart, the navigator echo should have an important role in the future of cardiac MR.

REFERENCES

1. Atkinson, D.J.; Edelman, R.R. Cineangiography of the Heart in a Single Breath Hold with a Segmented TurboFLASH Sequence. Radiology **1991**, *178*, 357–360.
2. Holland, A.E.; Goldfarb, J.W.; Edelman, R.R. Diaphragmatic and Cardiac Motion During Suspended Breathing: Preliminary Experience and Implications for Breath-Holding. Radiology **1998**, *209*, 483–489.
3. Ehman, R.L.; Felmlee, J.P. Adaptive Technique for High-Definition MR Imaging of Moving Structures. Radiology **1989**, *173*, 255–263.
4. Bogren, H.G.; Lantz, B.M.; Miller, R.R.; Mason, D.T. Effect of Respiration on Cardiac Motion Determined by Cineangiography. Implications Concerning Three-Dimensional Heart Reconstruction Using Computer Tomography. Acta. Radiol. Diagn. **1977**, *18*, 609–620.
5. Danias, P.G.; Stuber, M.; Botnar, R.M.; Kissinger, K.V.; Edelman, R.R.; Manning, W.J. Relationship Between Motion of Coronary Arteries and Diaphragm During Free Breathing: Lessons from Real-Time MR Imaging. AJR Am. J. Roentgenol. **1999**, *172,* 1061–1065.
6. Pauly, J.; Nishimura, D.G.; Macovski, A. A k-space Analysis of Small Tip-Angle Excitation. J. Magn. Reson. **1989**, *81*, 43–56.
7. Wang, Y.; Riederer, S.J.; Ehman, R.L. Respiratory Motion of the Heart: Kinematics and the Implications for the Spatial Resolution in Coronary Imaging. Magn. Reson. Med. **1995**, *33*, 713–719.
8. McConnell, M.V.; Khasigawala, V.C.; Savord, B.J.; Chen, M.H.; Chuang, M.L.; Edelman, R.R.; Manning, W.J. Prospective Adaptive Navigator Correction for Breath-Hold MR Coronary Angiography. Magn. Reson. Med. **1997**, *37*, 148–152.
9. Danias, P.G.; McConnell, M.V.; Khasigawala, V.C.; Chuang, M.L.; Edelman, R.R.; Manning, W.J. Prospective Navigator Correction of Image Position for Coronary MR Angiography. Radiology **1997**, *203*, 733–736.
10. Taylor, A.M.; Keegan, J.; Jhooti, P.; Firmin, D.N.; Pe

nell, D.J. Calculation of a Subject-Specific Adaptive Motion-Correction Factor for Improved Real-Time Navigator Echo-Gated Magnetic Resonance Coronary Angiography. J. Cardiovasc. Magn. Reson. **1999**, *1*, 131–138.

11. Nagel, E.; Bornstedt, A.; Hug, J.; Schnackenburg, B.; Oswald, H.; Fleck, E. Optimisation of Real-time Adaptive Navigator Correction for 3D Magnetic Resonance Coronary Angiography. Magn. Reson. Med. **1999**, *42*, 408–411.
12. Korin, H.W.; Farzaneh, F.; Wright, R.C.; Riederer, S.J. Compensation for the Effects of Linear Motion in MR Imaging. Magn. Reson. Med. **1989**, *12*, 99–113.
13. Ehman, R.L.; Felmlee, J.P. Adaptive Technique for High Definition MR Imaging of Moving Structures. Radiology **1989**, *173*, 255–263.
14. Keegan, J.; Gatehouse, P.D.; Yang, G.Z.; Firman, D.N. Adaptive Motion Correction of Interleaved Spiral Images and Velocity Maps: Implications for Coronary Imaging. Proceedings of the 15th Annual Meeting of the ESMRMB. MAGMA **1998**, *6*, Suppl. 1, 67.
15. Korin, H.W.; Ehman, R.L.; Riederer, S.J.; Felmlee, J.P.; Grimm, R.C. Respiratory Kinematics of the Upper Abdominal Organs: A Quantitative Study. Magn. Reson. Med. **1992**, *23*, 172–178.
16. Gierada, D.S.; Curtin, J.J.; Erickson, S.J.; Prost, R.W.; Strandt, J.A.; Goodman, L.R. Diaphragmatic Motion: Fast Gradient Recalled Echo MR Imaging in Healthy Subjects. Radiology **1995**, *194*, 879–884.
17. Sachs, T.S.; Meyer, C.H.; Irrarazabal, P.; Hu, B.S.; Nishimura, D.G.; Macovski, A. The Diminishing Variance Algorithm for Real-Time Reduction of Motion Artefacts in MRI. Magn. Reson. Med. **1995**, *34*, 412–422.
18. McConnell, M.V.; Khasgiwala, V.C.; Savord, B.J.; Chen, M.H.; Chuang, M.L.; Edelman, R.R.; Manning, W.J. Comparison of Respiratory Suppression Methods and Navigator Locations for MR Coronary Angiography. AJR Am. J. Roentgenol. **1997**, *168*, 1369–1375.
19. Stuber, M.; Botnar, R.M.; Danias, P.G.; Kissinger, K.V.; Manning, W.J. Submillimeter Three-Dimensional Coronary MR Angiography with Real-Time Navigator Correction: Comparison of Navigator Locations. Radiology **1999**, *212*, 579–587.
20. Sachs, T.S.; Meyer, C.H.; Pauly, J.M.; Nishimura, D.G.; Macovski, A. Coronary Angiography Using the Real-Time Interactive 3D DVA. Proceedings of Sixth Scientific Meeting of ISMRM, Sydney, **1998**, *20*.
21. Wang, Y.; Grimm, R.C.; Felmlee, J.P.; Riederer, S.J.; Ehman, R.L. Algorithms for extracting motion information from navigator echoes. Magn. Reson. Med. **1996**, *36*, 117–123.
22. Liu, Y.L.; Riederer, S.J.; Rossman, P.J.; Grimm, R.C.; Debbins, J.P.; Ehman, R.L. A Monitoring, Feedback, and Triggering System for Reproducible Breath-Hold MR Imaging. Magn. Reson. Med. **1993**, *30*, 507–511.
23. Wang, Y.; Grimm, R.C.; Rossman, P.J.; Debbins, J.P.; Riederer, S.J., Ehman, R.L. 3D Coronary MR Angiography in Multiple Breath-Holds Using a Respiratory Feedback Monitor. Magn. Reson. Med. **1995**, *34*, 11–16.
24. Keegan, J.; Gatehouse, P.D.; Taylor, A.M.; Yang, G.Z.; Jhooti, P.; Firmin, D.N. Coronary Artery Imaging on a Mobile 0.5-Tesla Scanner: Implementation of Real-Time Navigator-Echo Controlled Segmented k-space FLASH and Interleaved Spiral Sequences. Magn. Reson. Med. **1999**, *41*, 392–399.
25. Taylor, A.M.; Keegan, J.; Jhooti, P.; Gatehouse, P.D.; Firmin, D.N.; Pennell, D.J. Differences Between Normal Subjects and Patients with Coronary Artery Disease for Three Different MR Coronary Angiography Respiratory Suppression Techniques. J. Magn. Reson. Imaging. **1999**, *9*, 786–793.
26. Taylor, A.M.; Jhooti, P.; Wiesmann, F.W.; Keegan, J.; Firmin, D.N.; Pennell, D.J. MR Navigator Echo Monitoring of Temporal Changes in Diaphragm Position: Implications for MR Coronary Angiography. J. Magn. Reson. Imaging **1997**, *7* 629–636.
27. Lenz, G.W.; Haacke, E.M.; White, R.D. Retrospective Cardiac Gating: A Review of Technical Aspects and Future Directions. Magn. Reson. Imaging **1989**, *7*, 445–455.
28. Hofman, M.B.; Paschal, C.B.; Li, D.; Haacke, E.M.; van Rossum, A.C.; Sprenger, M. MRI of Coronary Arteries: 2D Breath-Hold vs 3D Respiratory-Gated Acquisition. J. Comput. Assist. Tomogr. **1995**, *19*, 56–62.
29. Sachs, T.S.; Meyer, C.H.; Hu, B.S.; Kohli, J.; Nishimura, D.G.; Macovski, A. Real-Time Motion Detection in Spiral MRI Using Navigators. Magn. Reson. Med. **1994**, *32*, 639–645.
30. Oshinski, J.N.; Hofland, L.; Mukundan, S.; Dixon, W.T.; Parks, W.J.; Pettigrew, R.I. Two-Dimensional Coronary MR Angiography Without Breath-Holding. Radiology **1996**, *201*, 737–743.
31. Maki, J.H.; Prince, M.R.; Londy, F.J.; Chenevert, T.L. The Effects of Time Varying Intravascular Signal Intensity and k-space Acquisition Order on Three-Dimensional MR Angiography Image Quality. J. Magn. Reson. Imaging **1996**, *6*, 642–651.
32. Jhooti, P.; Keegan, J.; Gatehouse, P.D.; Collins, S.; Rowe, A.; Taylor, A.M.; Firmin, D.N. 3D Coronary Artery Imaging with Phase Reordering for Improved Scan Efficiency. Magn. Reson. Med. **1999**, *41*, 555–562.
33. Sinkus, R.; Bornert, P. Motion Pattern Adapted Real-Time Respiratory Gating. Magn. Reson. Med. **1999**, *41*, 148–155.
34. Sinkus R.; Bornert, P. Extension of Real-Time MR Gating to Cope with Changes in Motion Pattern: Making MR Gating Autarkic. Proceedings of Sixth Scientific Meeting of ISMRM Sydney, 1998, 2127.

Received June 21, 2000
Accepted January 11, 2001

Marcel Dekker, Inc.
270 Madison Avenue, New York, New York 10016

Request Permission or Order Reprints Instantly!

Interested in copying and sharing this article? In most cases, U.S. Copyright Law requires that you get permission from the article's rightsholder before using copyrighted content.

All information and materials found in this article, including but not limited to text, trademarks, patents, logos, graphics and images (the "Materials"), are the copyrighted works and other forms of intellectual property of Marcel Dekker, Inc., or its licensors. All rights not expressly granted are reserved.

Get permission to lawfully reproduce and distribute the Materials or order reprints quickly and painlessly. Simply click on the "Request Permission/Reprints Here" link below and follow the instructions. Visit the U.S. Copyright Office for information on Fair Use limitations of U.S. copyright law. Please refer to The Association of American Publishers' (AAP) website for guidelines on Fair Use in the Classroom.

The Materials are for your personal use only and cannot be reformatted, reposted, resold or distributed by electronic means or otherwise without permission from Marcel Dekker, Inc. Marcel Dekker, Inc. grants you the limited right to display the Materials only on your personal computer or personal wireless device, and to copy and download single copies of such Materials provided that any copyright, trademark or other notice appearing on such Materials is also retained by, displayed, copied or downloaded as part of the Materials and is not removed or obscured, and provided you do not edit, modify, alter or enhance the Materials. Please refer to our Website User Agreement for more details.

Order now!

Reprints of this article can also be ordered at
http://www.dekker.com/servlet/product/DOI/101081JCMR100107467