TOPICS

- Key Hole Acquisition
- Block Regional Interpolation Scheme for K-space (BRISK)
- Time Resolved Imaging of Contrast Kinetics (TRICKS)
- Real Time Imaging

Introduction

Time-resolved study to image dynamic or time-varying processes such as cardiac motion, fMRI task activation, catheter tracking, etc.

Spatial Resolution

Spatial Coverage

Temporal Resolution

Partial k-space Updating

Involve reconstruction processing that recover some spatial resolution and coverage

Spatial Resolution Compromised

Key-hole, BRISK and TRICKS

Spatial Coverage Compromised

Reduced FOV (rFOV)

- rFOV might be more effective for Cardiac Imaging

Keyhole Acquisition

Based on assumption that dynamic information is band-limited in k-space.

Key-hole was initially introduced to improve the temporal resolution of contrast-enhanced imaging based on assumption that contrast bolus is contained in the low spatial frequencies and that high spatial frequencies is relatively static.

Data Acquisition :

Small number of views – *keyhole data.* They are collected symmetrically over the centre of k-space.

Full number of views - *reference data.* They are collected usually before (some cases during or after) the collection of the keyhole data.

Keyhole data ≈ 25 % Reference data

Keyhole data + Reference data = Complete k-space data

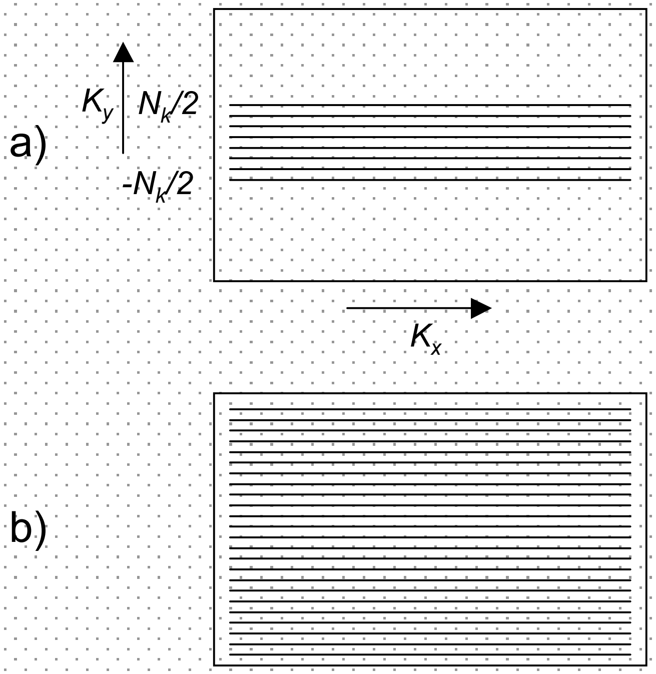


Fig1. a) 8 keyhole views b) 32 reference views

Keyhole Acquisition

To obtain MR images by the keyhole method, a full set of k-space data is acquired only once as reference data

To accelerate acquisition time, some of the k-space data, the keyhole data, is continuously updated for images of different cardiac phases

A central part of the reference data is replaced by each set of keyhole data to yield an approximation of a complete k-space data set

For consistency of data, the power of the keyhole data is adjusted to the reference data.

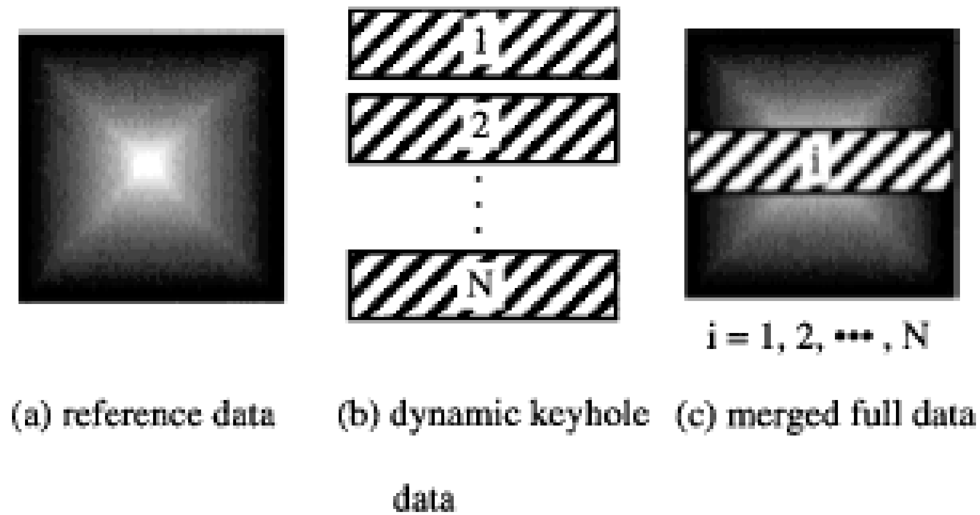
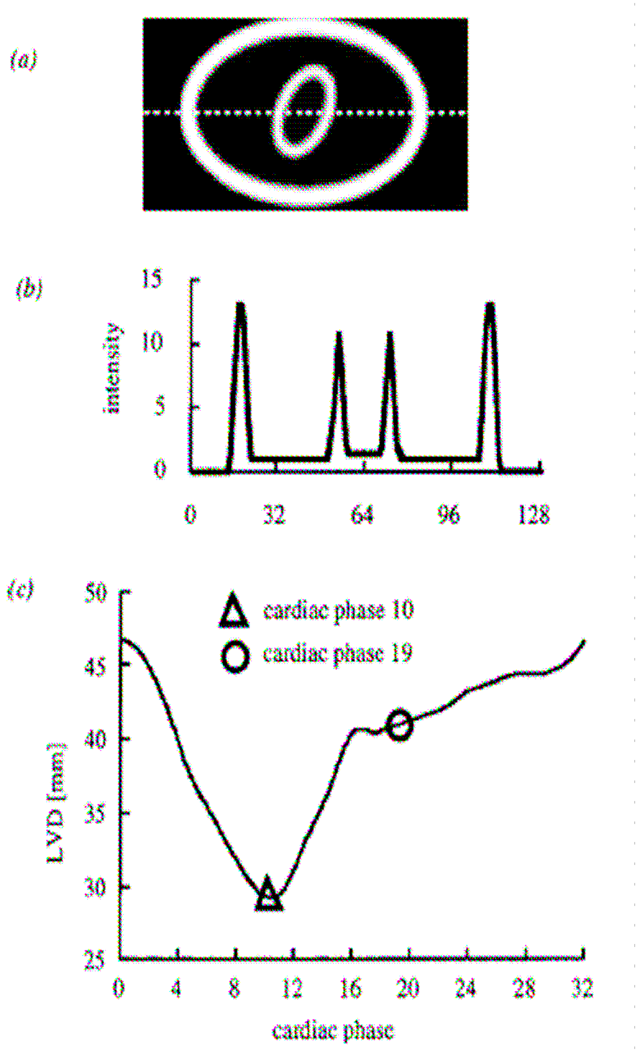


Figure 2. a: Reference data. A full set of the k-space data is acquired only once. **b:** Dynamic keyhole data. The keyhole data is updated for various cardiac phases. **c:** Merged full data. The keyhole data is combined with reference data to yield complete k-space data sets corresponding to various cardiac phases.

Keyhole Acquisition

Model for the computer simulation. a: Shape of the left ventricular model. b: Profile of signal intensity at the dotted line in a. c: Temporal change of left ventricular diameter. The center part of the model (64 3 64) is used for the computer simulation.



Keyhole Acquisition

Ideally, the extent of the keyhole is determined by the size of the smallest dynamic object to be resolved. For a given keyhole size, the smaller the object, the greater the error in the reconstructed image. For 3D acquisition, keyhole methods can be used in the phase-encoded, the slice-encoded direction, or both. Because spatial resolution in the slice-encoded direction is usually lower than in the phase direction.

Keyhole data in the slice-encoded direction ≥ 50%.

Reconstruction :

• *Substitution Method*

Reference k-space data are substituted for the missing high spatial frequencies of the keyhole data set to create composite k-space data

$$\widehat{S}(k_m) = \begin{cases} S_{keyhole}(k_m) & -N_k/2 \le m < N_k/2 \\ S_{reference}(k_m) & otherwise \end{cases}$$

where $S_{keyhole}$ and $S_{reference}$ are keyhole and reference raw data, respectively; m is the index of the phase encode line number k_m; and N_k is the number of keyhole views

Keyhole Acquisition

- *Weighted Substitution Method*

The discontinuity between $S_{keyhole}$ and $S_{reference}$ is reduced by using a weighted combination of pre- and postcontrast references S_{pre} and S_{post} :

$$\widehat{S}(k_m) = \begin{cases} S_{keyhole}(k_m) & -N_k/2 \le m < N_k/2 \\ w_{pre} S_{pre}(k_m) + w_{post} S_{post}(k_m) & otherwise \end{cases}$$

W_{pre} and w_{post} are obtained by least-square of the following equations for each acquisition of $S_{keyhole}$:

$$S_{keyhole}(k_m) = w_{pre} S_{pre}(k_m) + w_{post} S_{post}(k_m) \quad -N_k/2 \le m < N_k/2$$

Keyhole Acquisition

- *Generalized Series Method*

The discontinuity is reduced by reconstructing the image from basis fuctions that incorporate a priori information from the refernce image. The reconstructed image is given by :

$$I_{GS(y)} = \sum_{m=N_k/2}^{N_k/2-1} c_m \phi_m(y) \qquad \phi_m(y) = \left| I_{ref}(y) \right| e^{i2\pi k_m y}$$

where Øm is the basis functions and I_{ref} is the reference image.

$$S_{keyhole}(k_m) = \sum_{n=-N_k/2}^{N_k/2-1} c_n S_{ref}(k_{|m-n|}) \qquad -N_k/2 \le k < N_k/2$$

The coefficients c_m are determined by requiring that the measured data within the keyhole $S_{keyhole}(k_m)$ equal the resulting k-space data found from Fourier transforming I_{GS}. It is straightforward to show that this constraint results in the relation.

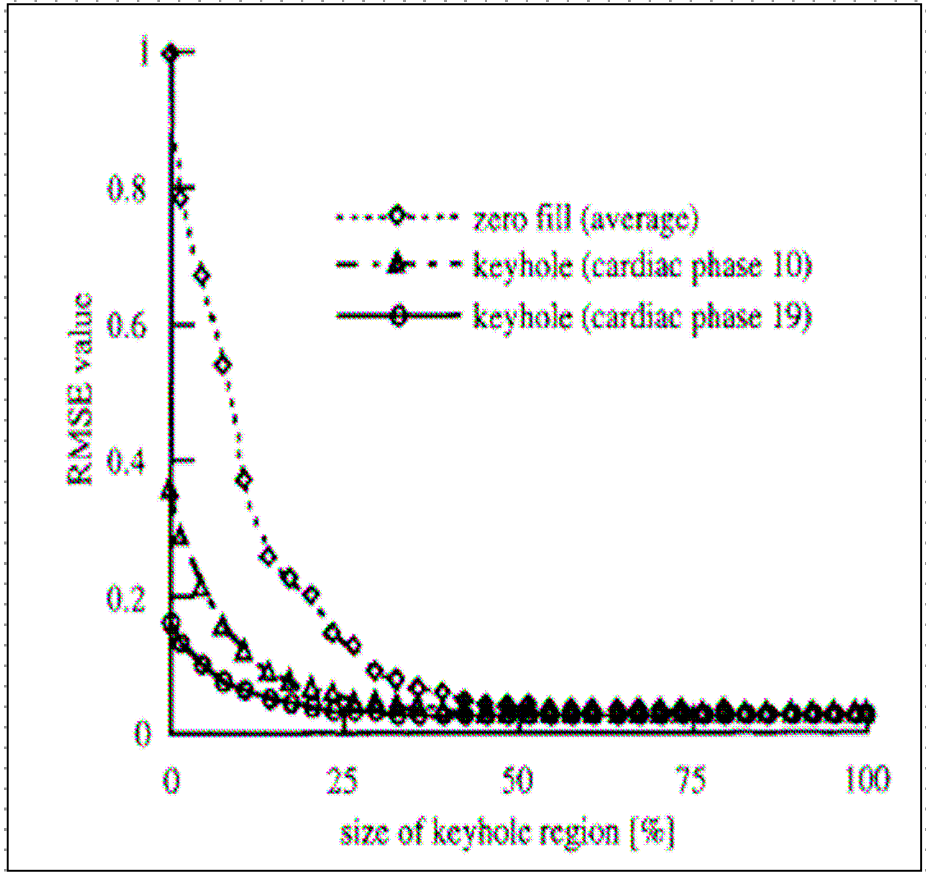
Keyhole Acquisition

Figure shows the relationship between RMSE values and the size of the keyhole region.

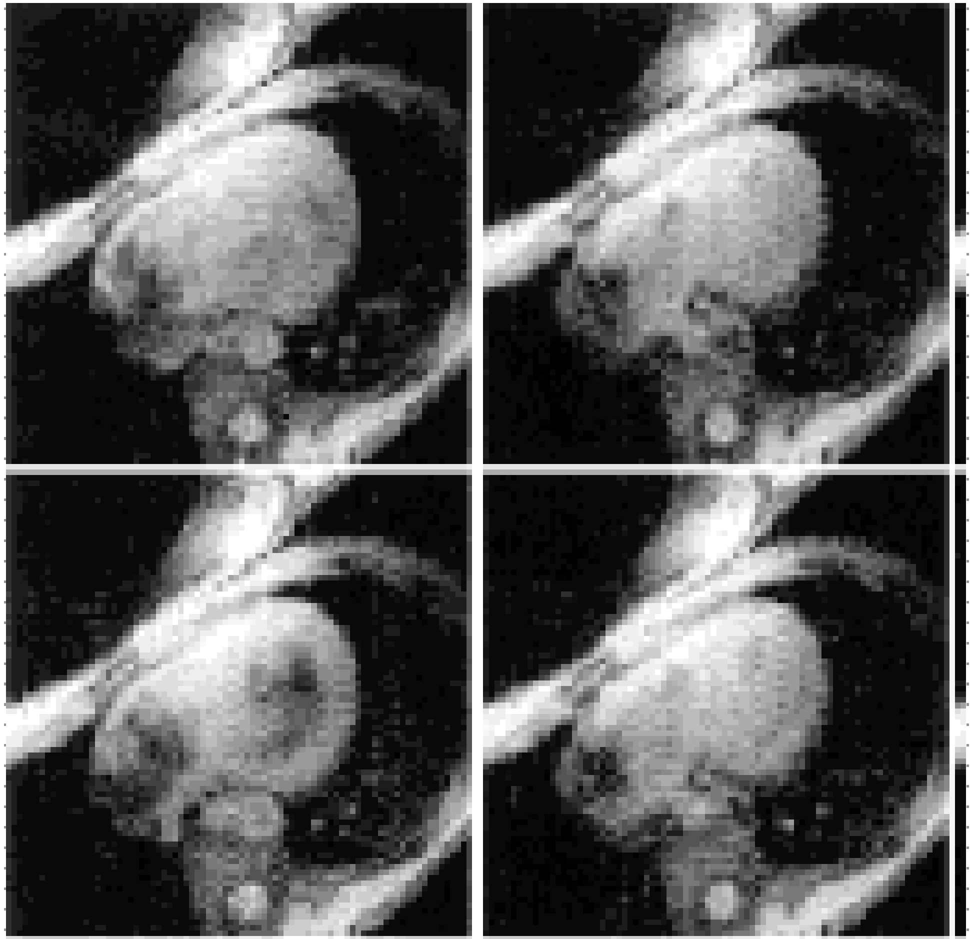
The error values of keyhole images are always smaller than those of zero-filled images.

The choice of cardiac phase used for reference data affected RMSE values, particularly when the size of the keyhole region was less than 25%. RMSE values for keyhole regions larger than 25% were almost constant.

When the size was less than 25%, a substantial increase in the RMSE value is noted.

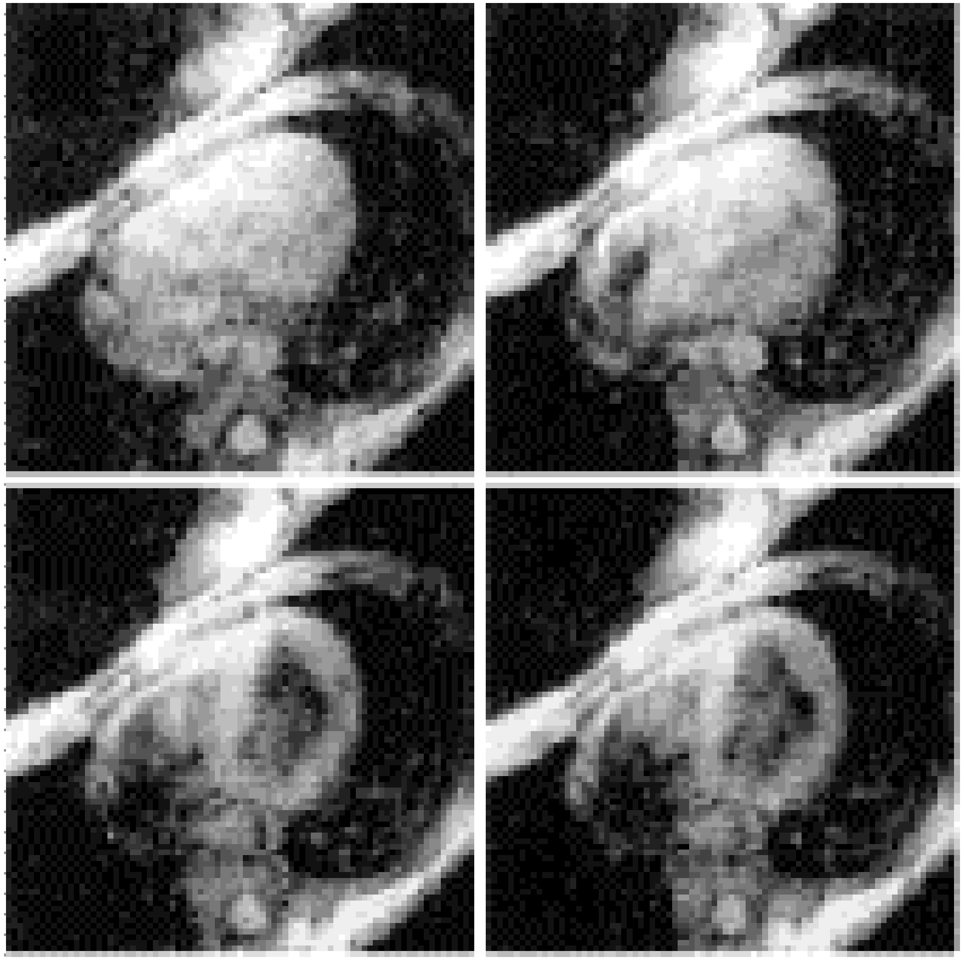


Keyhole Acquisition



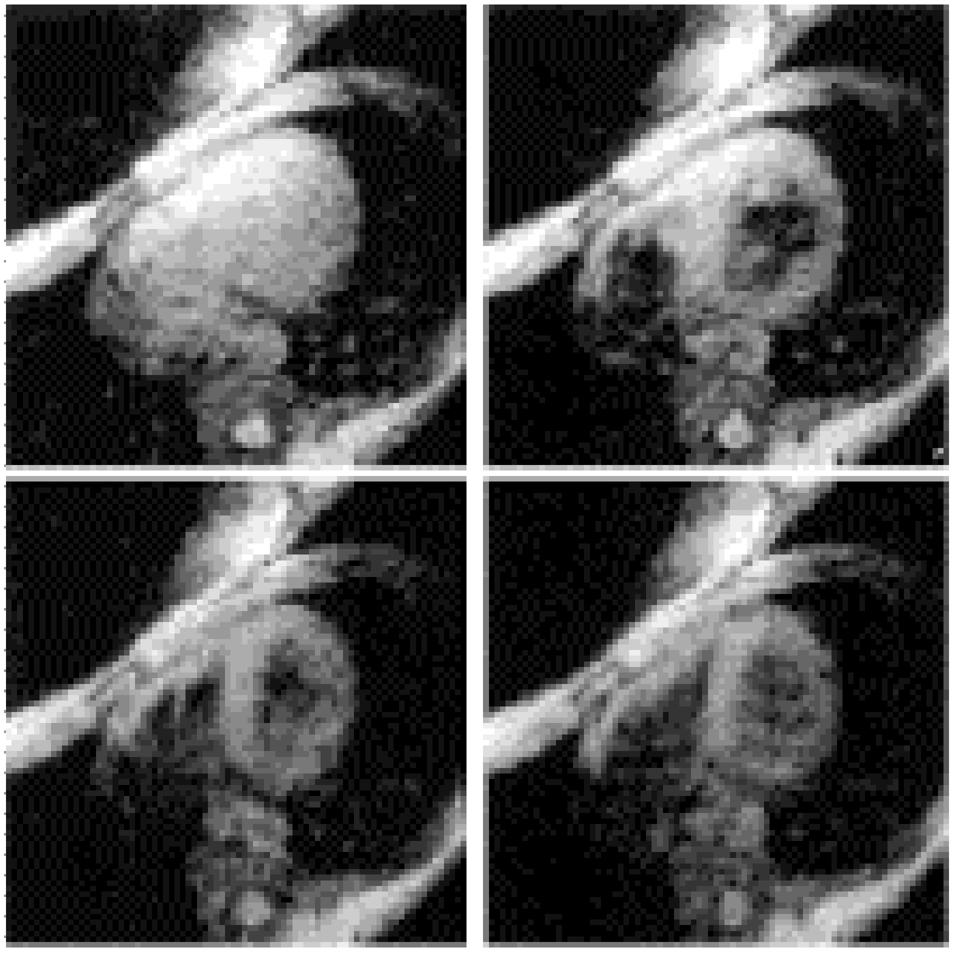
a) The conventional fast gradient echo imaging (323 msec/image)

Keyhole Acquisition



b) Keyhole imaging (keyhole data 25%; 88 msec/image)

Keyhole Acquisition



b) Keyhole imaging (keyhole data 50%; 176 msec/image)

Keyhole Acquisition

Applications :

- fMRI
- Cardiac Imaging
- Contrast Enhanced Imaging

Studies suggest that keyhole acquisition should be applied cautiously for quantitative assessment of contrast kinetics. One study showed that keyhole acquisition introduces substantial errors into the calculation of contrast kinetic model parameters, even though the reconstructed images appear artifact free.

BRISK

Block **R**egional **I**nterpolation **S**cheme for **K**-space **(BRISK)**

Extension of the fundamental key-hole idea that edges of k-space need less frequent updating than the center when tracking most dynamic processes.

Originally developed to shorten acquisition time with 2D Multi phase cardiac scans that do not use segmented k-space acquisition.

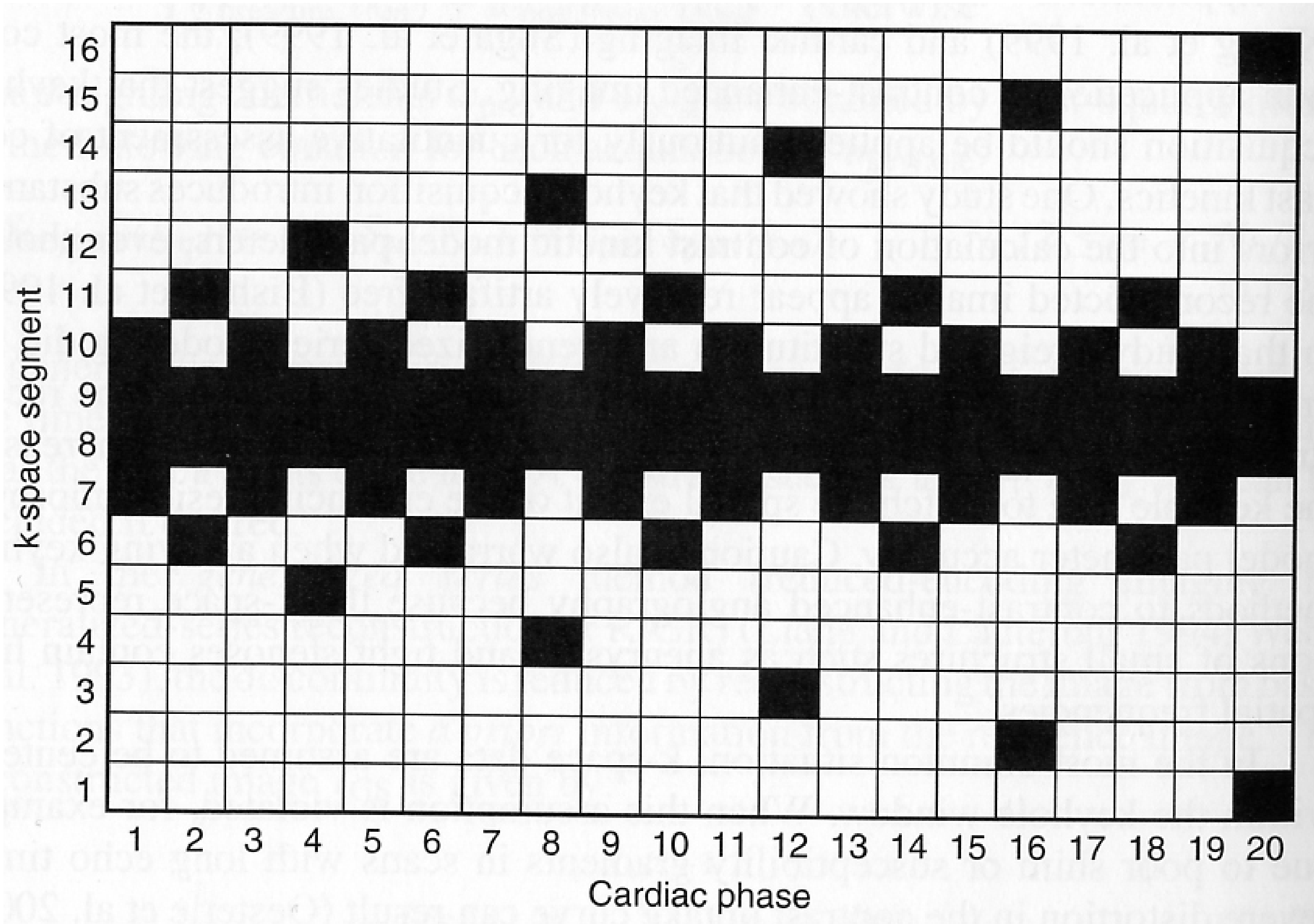
Conventional scan, one view of k-space is acquired N_{cp} times per heart beat for each slice, where N_{cp} is the cardiac phases.

Heart beats required to acquire full k-space data = number of k-space lines

If heart beat = 80 beats/minute and 256 phase-encoding lines.

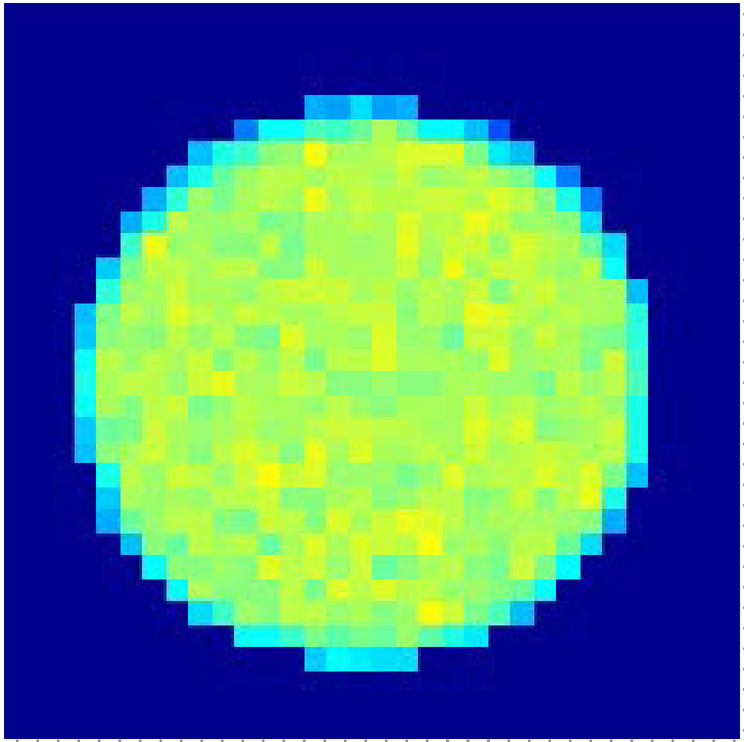
The number of heartbeats is 256 X 60/80 = 192s (3 min 12 Seconds) per slice.

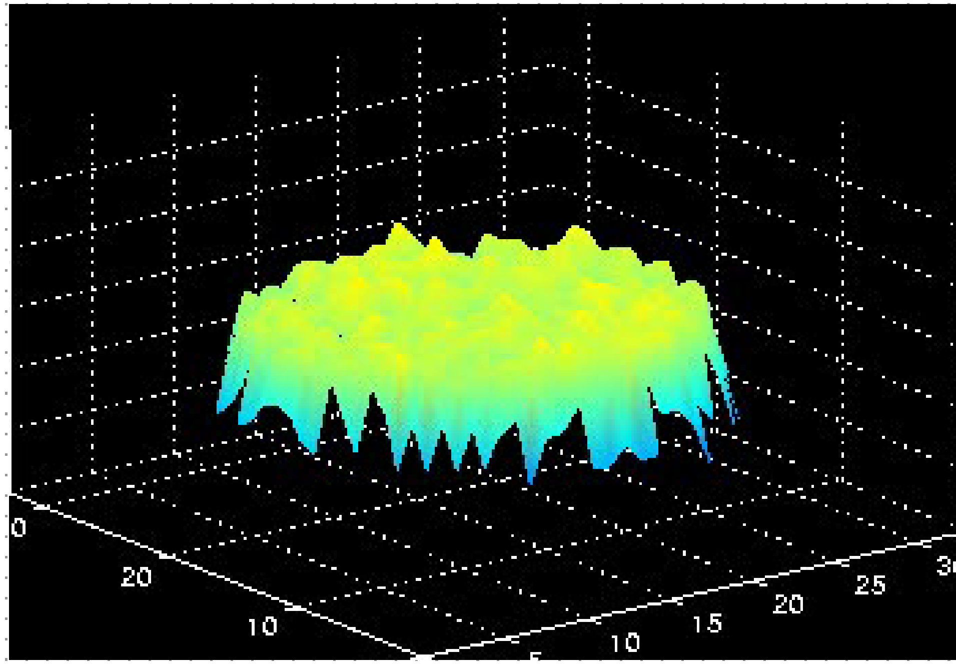
BRISK



BRISK k-space sampling schedule

BRISK





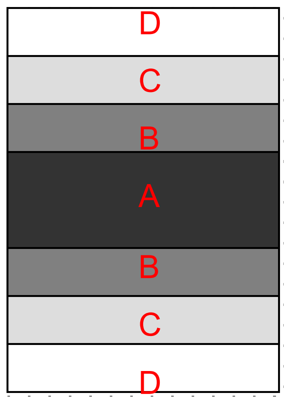
TRICKS

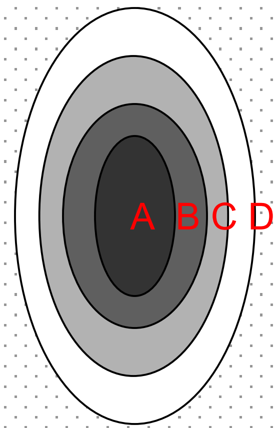
Time **R**esolved **I**maging of **C**ontrast **K**inetic**S** (**TRICKS**)

Usually applied to improve the time resolution of 3D contarts-enhanced scans.

Center area of k-space is acquired with the highest temporal frequency.

$k_y - k_z$ plane is divided into equal areas that are cyclically sampled in time. $k_y - k_z$ plane was divided only in the k_y direction (shown in fig1), but more recent work uses an elliptical-centric division (shown in fig2).





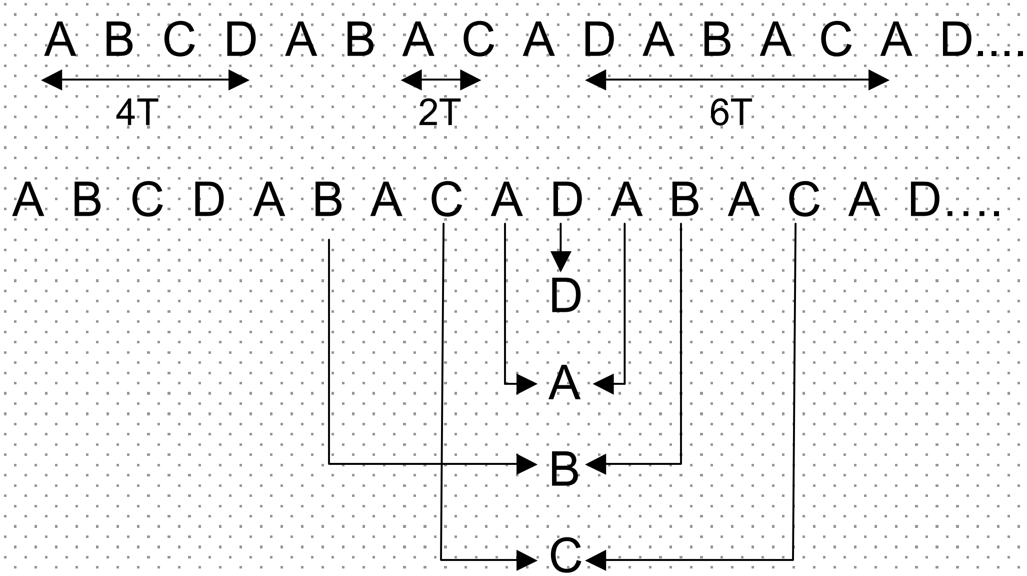
Usually divided in four divisions A,B,C and D; where section A corresponds to the center of k-space.

The resulting image can be used as a mask for subtraction.

The four sections are acquired in the order **ABACADABACAD…**

TRICKS

Time to acquire all four segments 4T, then segment A is acquired at intervals 2T, whereas segments B,C and D are acquired at intervals 6T(shown in figure 3)



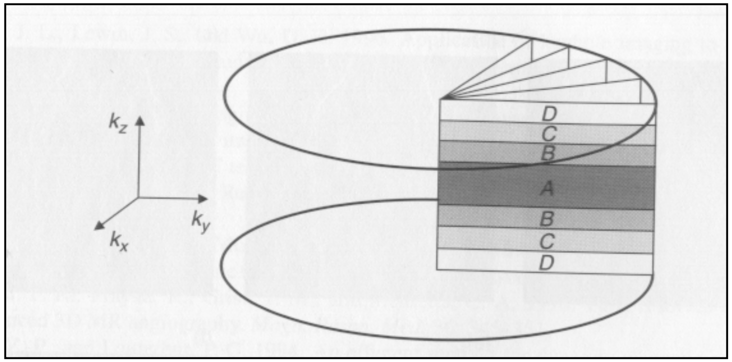
Thus segment A is used in the reconstruction with temporal resolution 2T, whereas segments B,C and D are used for temporal resolution 6T.

What is the effect on temporal resolution ?

Temporal resolution for center of k-space increases from 4T to 2T

TRICKS

3D PR-TRICKS, uses stacked projection acquisition, that is, projection acquisition within k_x-k_y plane along with Fourier encoding in the slice-encoded direction k_z. Here, TRICKS is applied to the k_z direction, which is divided into equals segments. (shown in figure 4)



TRICKS is more difficult to apply to scans requiring breath-holding, such as imaging aorta and renals arteries. The breath-holding must be timed to coincide with the scans and bolus arrival and therefore requires either a timing bolus or other synchronization method. For contrast-enhanced imaging of the carotid, vertebral and basilar arteries, the temporal resolution of conventional TRICKS is sometimes insufficient because of the fast venous return that causes jugular enhancement.

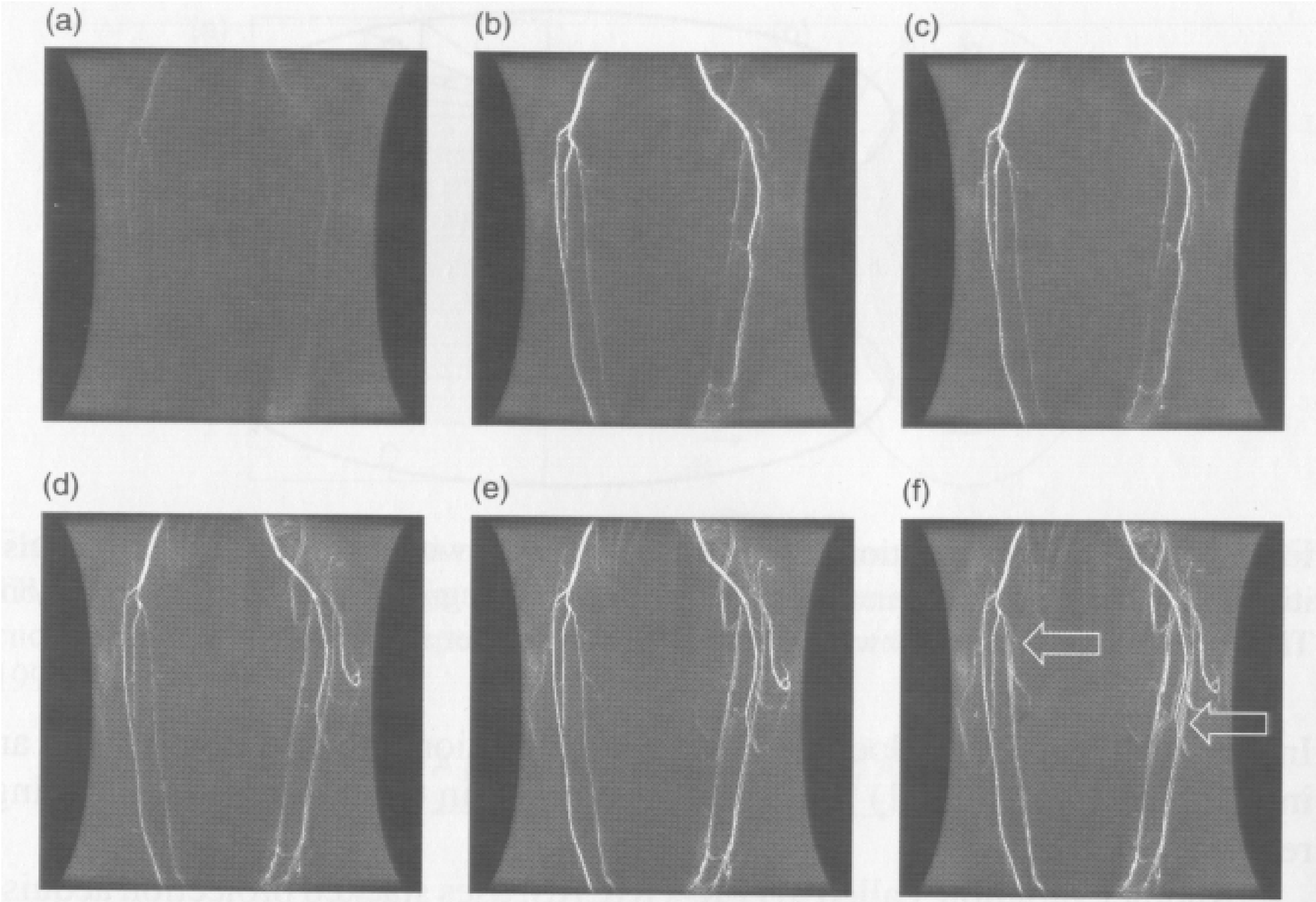
Faster methods such as PR-TRICKS with angular undersampling can be used.

TRICKS

Applications :

Bilateral imaging of the vessels of the lower legs. With relatively slow flow in the legs, the temporal resolution allowed by TRICKS is sufficiently good that a timing bolus is usually not needed. Each image is a maximum intensity projection of a stack of coronal slices. The interval between frames is T=13.2s, giving a true temporal resolution of 2T=26.4s for the center of k-space(segment A). In this example without TRICKS, the temporal resolution would be 4T=52.8s and would be insufficient to reliablyy capture the peak arterial phase.

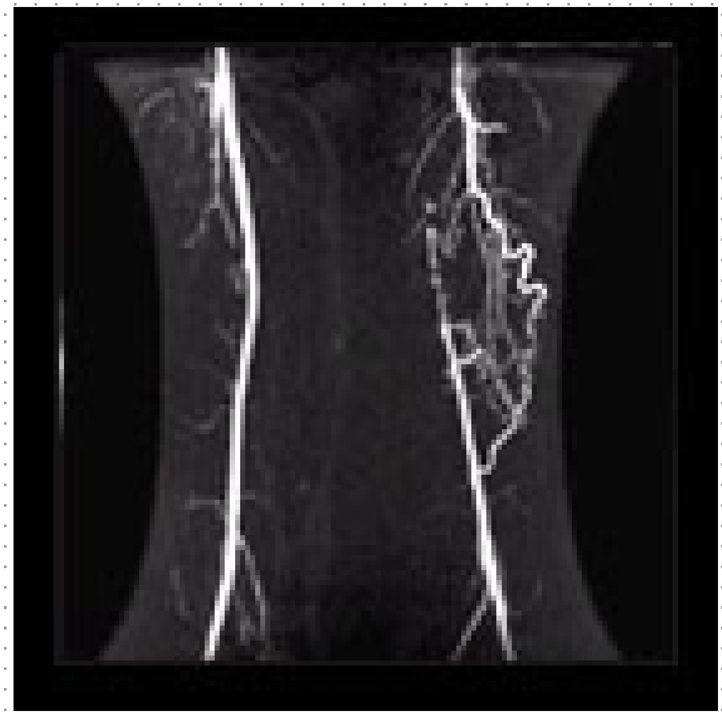
TRICKS



TRICKS

TRICKS used to image the vessels of the leg.

TRICKS used to image coronal vessels.



Real-Time Imaging

For high-frame rates also termed as MR Fluoroscopy. A real-time MRI acquisition has the ability to :

- continually acquire data
- rapidly reconstruct and display the resulting images
- provide the operator control to interactively alter the image acquisition based on the displayed images.

Terminology

Temporal resolution is measured in frames per second or in hertz. For a 2D phase-encoded acquisition the true temporal resolution is given by the expression:

$$R = \frac{1}{N_{shot} * TR * N_{EX}}$$

Where N_{shot} is the number of RF excitations per complete k-space traversal, and N_{EX} is the number of signal averages. Note that for a standard 2D Fourier acquisition, the number of shots is simply equal to the number of phase-encoding lines, $N_{shot}=N_{phase}$.

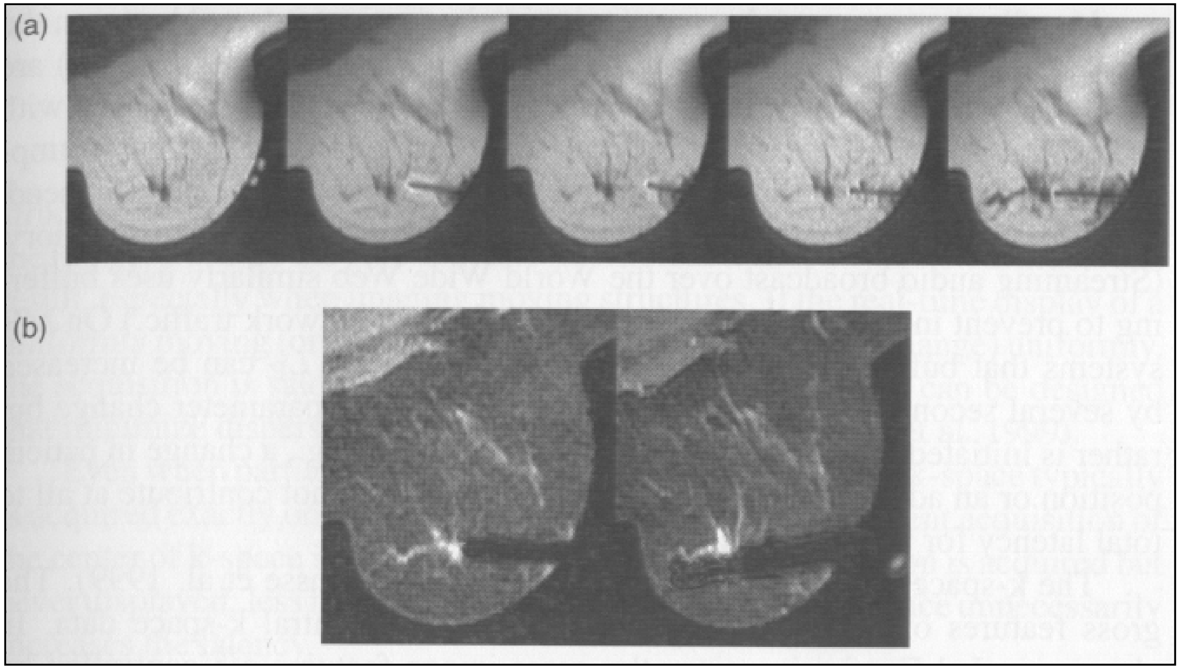
The use of rectangular FOV, parallel imaging and partial Fourier acquisition all can increase the true temporal resolution because each reduces N_{shot}. Parallel imaging reconstruction and partial Fourier reconstruction, however, both increase computational complexity, so the temporal resolution improvement is only useful if the reconstruction engine can keep pace.

Real-Time Imaging

Real-time acquisitions are also characterized by their frame-rate, which is the number of images reconstructed and displayed per second, measured in Hz or frames per second.

Sometimes the frame rate is called the apparent or effective, temporal resolution.

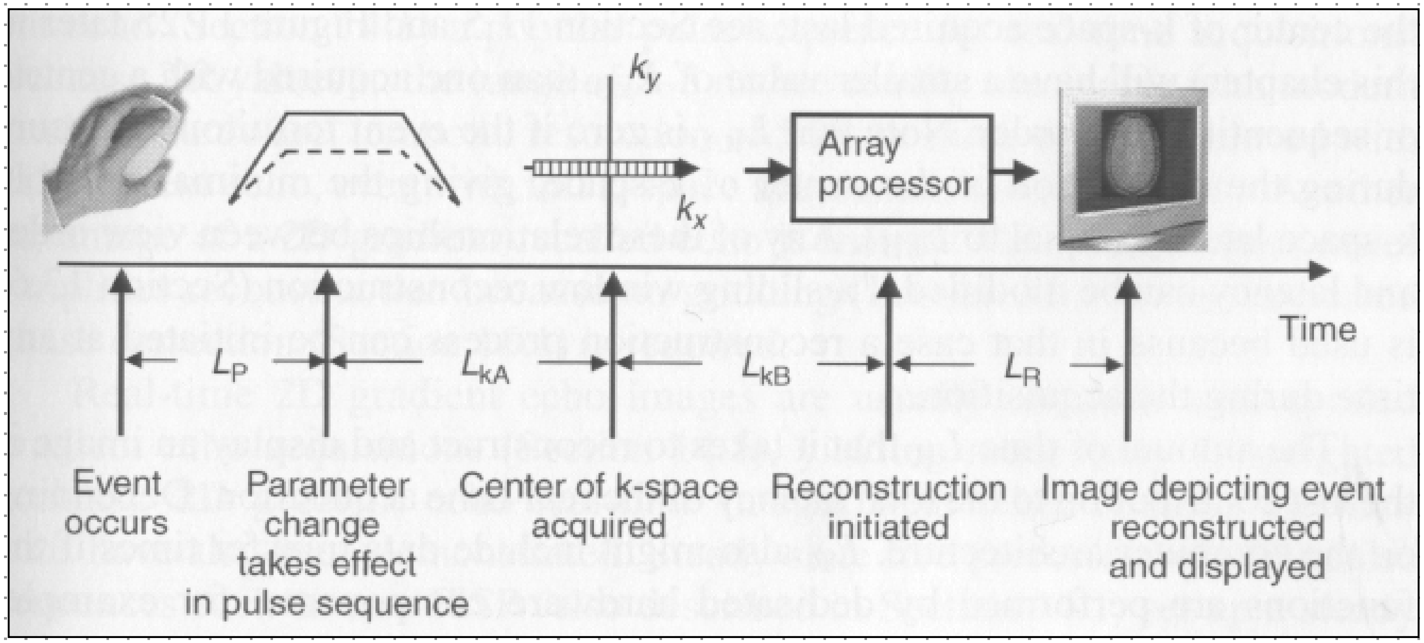
The frame rate can be greater than the true temporal resolution if a partial k-space updating technique is used. Frame rate in the 1-10 fps range are commonly achieved with real time MRI.



Real-Time Imaging

***Lag* or *latency* :**

Latency is defined as the time interval between when an event occurs and when an operator viewing the real-time images can first detect it. If the latency is too long, the operator often makes a second parameter adjustment before the first one has worked its way through the system.



Real-Time Imaging

The total latency has several contributions, which are schematically depicted in the time line.

If the event is an operator-initiated command to change a parameter, then the command takes some finite amount of time L_p to be recognized and played by the pulse-sequence hardware that controls the gradients and RF.

The total latency is given by :

$$L_T=L_P+L_{KA}+L_{KB}+L_B$$

Real-Time Imaging

2D Gradient Echo

Its simplicity, robustness and speed make 2D gradient echo a popular pulse sequence for real-time acquisitions. Because TR values in the range 2-5 ms are readily obtained with modern gradient hardware, temporal resolution of 5fps or more can be achieved with 2D gradient echo, even with full k-space acquisition. Another advantage of a 2D gradient recalled echo is that the Cartesian k-space raster simplifies reconstruction because no gridding or sophisticated phase correction is required.

Real-time 2D gradient echo images are usually obtained with spoiled gradient echo acquisitions, yield moderately T1-weighted contrast. 2D gradient echo real-time images with other contrast mechanisms have also been demonstrated.

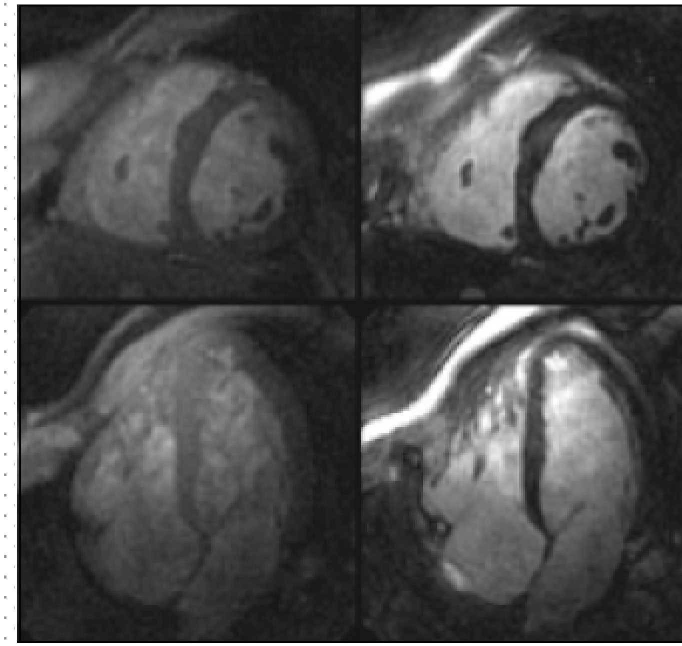


Figure 1. Cardiac images acquired at 1.5T using (*left*) spiral gradient-recalled echo [9•] and (*right*) spiral steady-state free precession (SSFP) sequences [17]. Notice the substantially higher signal to noise ratio, improved blood-myocardium contrast, and reduced in-plane flow artifacts achieved with SSFP.

Real-Time Imaging

Steady-state free precession (SSFP) pulse sequences such as true FISP set up a steady state not only for the longitudinal but also for the transverse magnetization. This class of pulse sequence has the advantage of producing a more intense signal and the option of obtaining a bright fluid signal. One issue is that the steady state can take longer to establish than in the spoiled pulse sequences, which can be problmatic for some dynamic imaging. True FISP has generally proved to be robust for cardiac imaging.

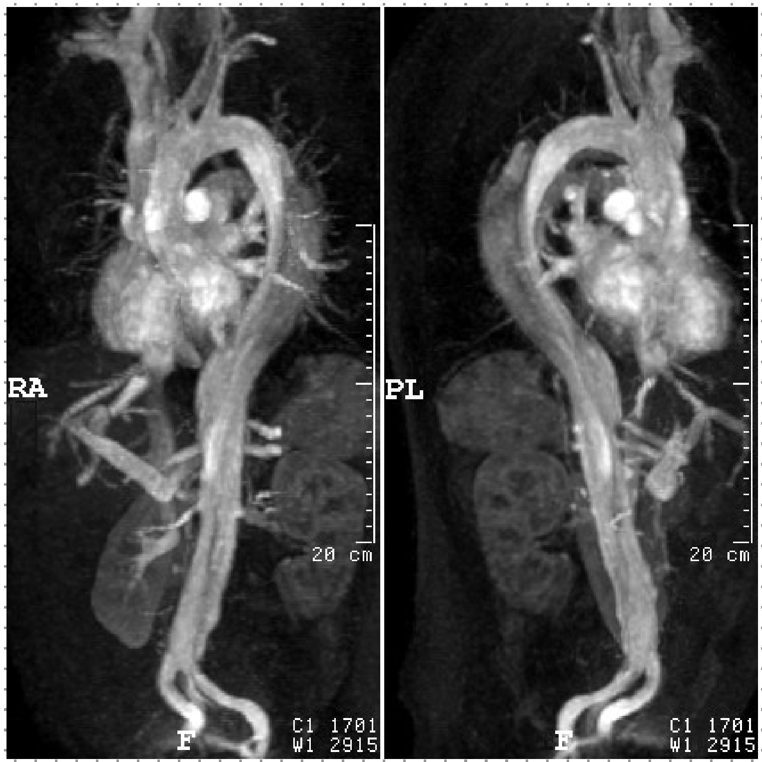
Real-Time Imaging

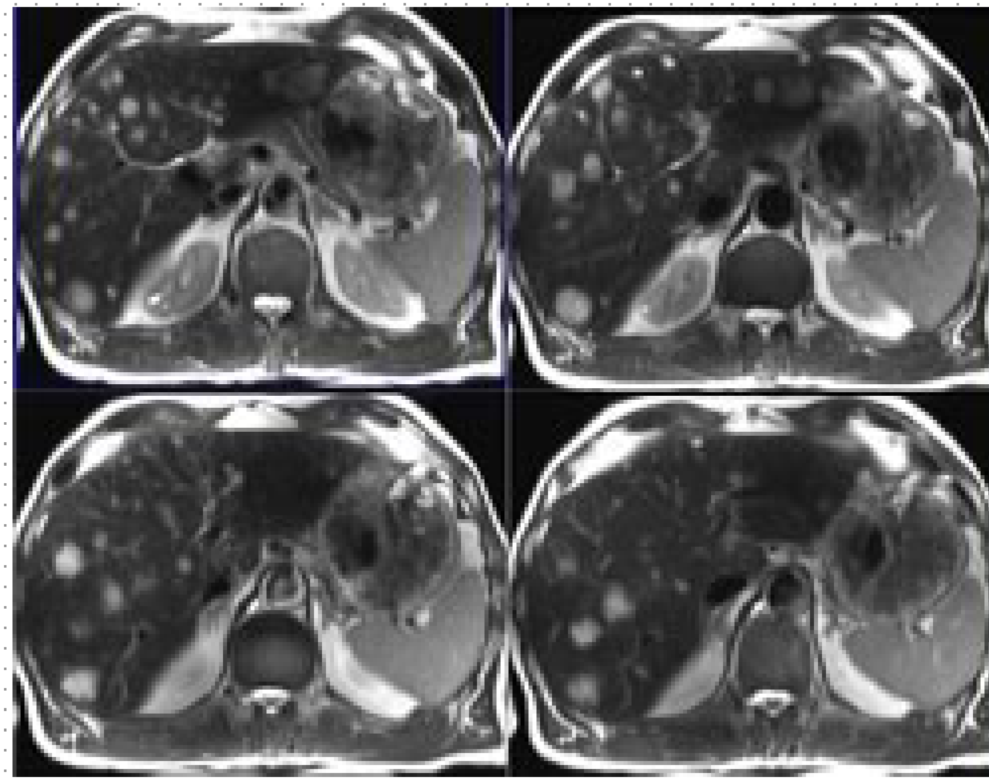
HASTE

In some applications gradient echo acquisitions are suboptimal because contrast weighting obtained only with RF spin echoes is desired, susceptibility artifacts cannot be tolerated, or both. For standard RF spin echo, however, the temporal resolution is too slow for the majority of real-time applications, so echo train methods are used instead. In order to increase the frame rate to the range of 1-2 fps, half-Fourier acquired single turbo spin echo can be used.

The string of refocusing pulses required for HASTE carries considerable RF energy, especially at field strengths of 1.5T or higher. Even in non-real time HASTE applications, the flip angle of the refocusing pulses is usually reduced from 180º to a value in the range of 120-160º. To further minimize patient heating, several additional strategies can be employed in real-time applications. These include varying the flip angle of the refocusing pulses as a function of position in the echo train and only acquiring an updated image when the operator makes a parameter change

Real-Time Imaging



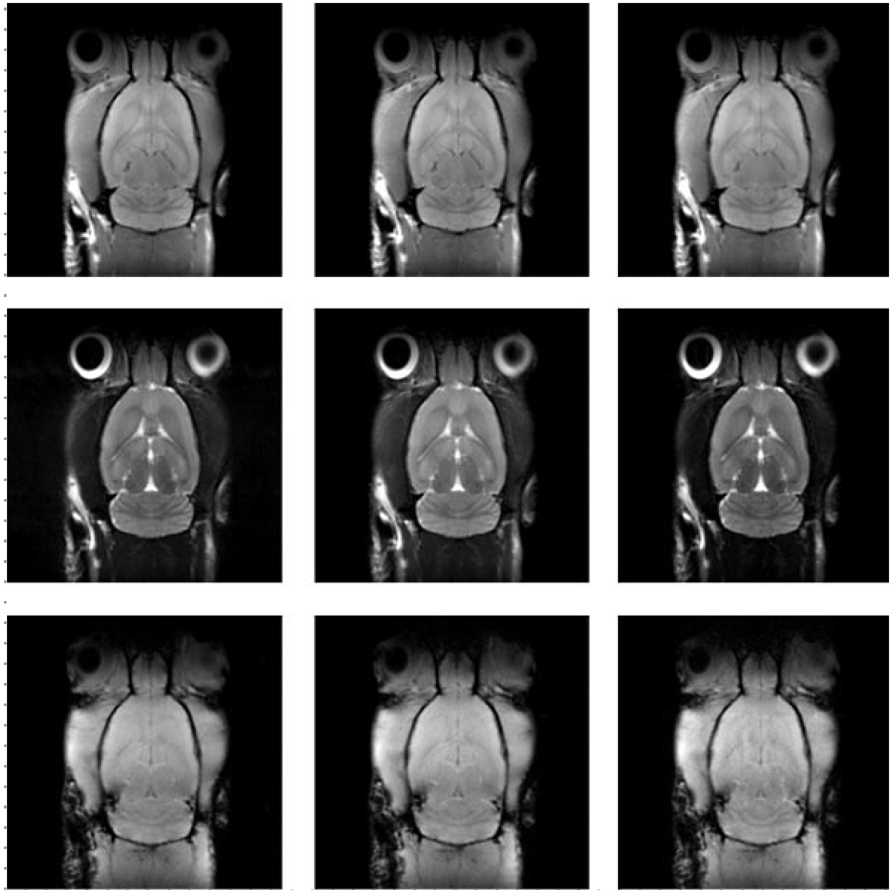


Images using HASTE

Real-Time Imaging

Parallel-Imaging Reconstruction

Parallel-imaging methods that reduce the number of phase-encoding steps can be used to increase the true temporal resolution. In standard, non-real-time applications, SENSE is one of the most widely used parallel-imaging techniques. Its use for real-time imaging is more challenging because the reconstruction time is prolonged, because of not only the high number of receiver channels but also the complexity of the SENSE reconstruction time is prolonged, because of not only the high number of receiver channels but also temporal resolution can be limited by the reconstruction. Unaliasing by Fourier encoding the overlaps using the temporal dimension (UNFOLD) is a parallel-imaging technique that is specifically designed to operate on time-series of images and does not required multiple receiver channels.



Real-Time Imaging

M-Mode Imaging

In motion-mode (M-mode) ultrasound, the vertical axis of the gray-scale display is a spatial dimension and the horizontal axis represents time. Because only one spatial dimension is acquired, very high temporal resolution can be obtained. Real-time MRI has an analogus M-Mode acquisition. The MR M-mode imaging acquisition usually employs a two-dimensional RF spiral exciatation pulse that excites a pencil-beam shaped volume. A gradient echo read out then provides spatial encoding along the long axis of the beam. No phase encoding is applied, so the resulting image is a line scan that has only one spatial dimension.
N_{shot}=1; TR is short implies that very high true temporal resolution can be achieved, even with signal averaging.

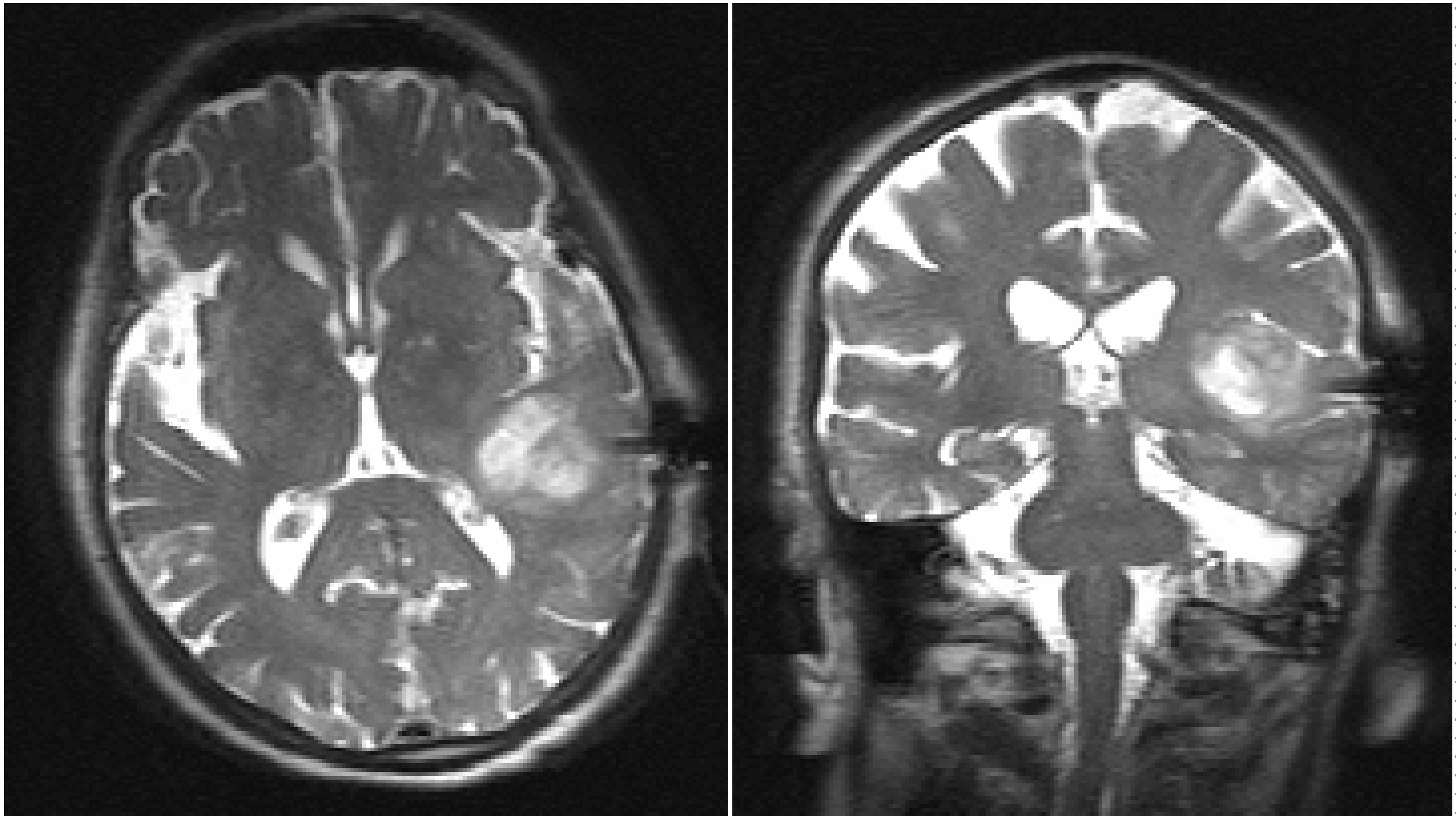
Real-Time Imaging

Applications of Real-Time MRI

Interactive scan plan prescription

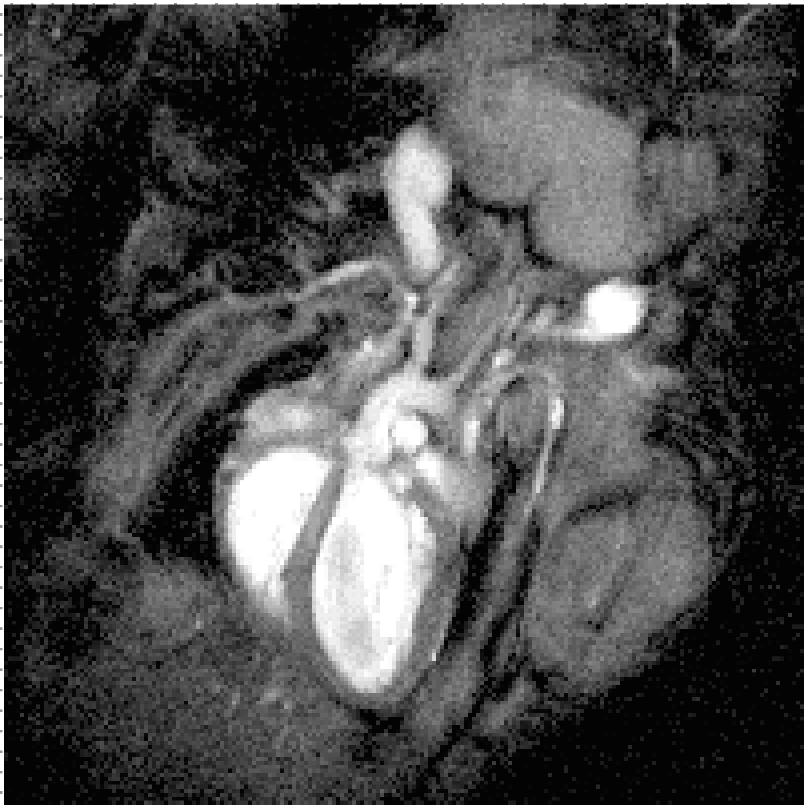
Fluoroscopically triggered MR Angiography

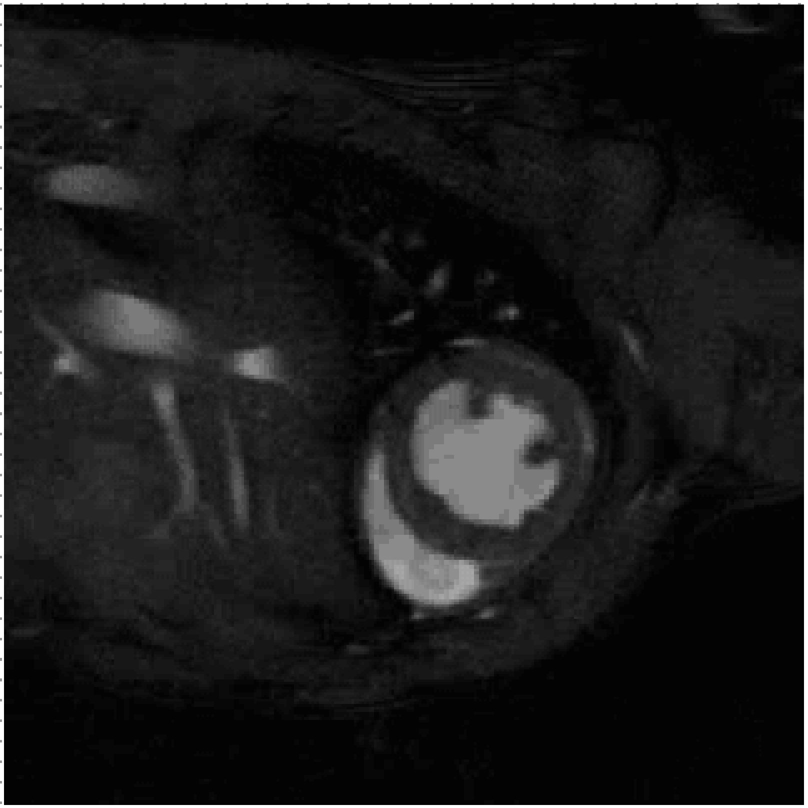
Real-Time Imaging



Real time MRI of Biopsy Procedure

Real-Time Imaging





2D Cine-MR Images

Beating Mouse Heart (Four Chamber View)

Beating Mouse Heart (Short Axis View)

REFERENCES

[1] Handbook of MRI Pulse Sequences; Matt A. Bernstein, Kevin F. King, Xiaohong Joe Zhou, 2004

[2] Mikio Suga, Tetsuya Matsuda, Masaru Komori, Kotaro Minato, And Takashi Takahashi; Keyhole Method For High-speed Human Cardiac Cine MR Imaging; Journal Of Magnetic Resonance Imaging 10:778–783 (1999).

[3] Eun-Kee Jeong, Seong-Eun Kim, Junyu Guo, Eugene G. Kholmovski, and Dennis L. Parker; High-Resolution DTI with 2D Interleaved Multislice Reduced FOV Single-Shot Diffusion-Weighted EPI (2Dss-rFOV-DWEPI); Magnetic Resonance in Medicine 54:1575–1579 (2005)

[4] Eduardo Kortright, Mark Doyle, Andreas S. Anayiotos, Edward G. Walsh, Anthon R. Fuisz, and Gerald M. Pohost; Validation of Rapid Velocity Encoded Cine Imaging of a Dynamically Complex Flow Field Using Turbo Block Regional Interpolation Scheme for *k* Space; *Annals of Biomedical Engineering,* Vol. 29, pp. 128–134, 2001

[5] Pedro A. Rivas, Krishna S. Nayak, Greig C. Scott, Michael V. McConnell, Adam B. Kerr, Dwight G. Nishimura, John M. Pauly, and Bob S. Hu; In Vivo Real-Time Intravascular MRI; Journal of Cardiovascular Magnetic Resonance, 4(2), 223–232 (2002)

REFERENCES

[6] *Krishna S. Nayak and Bob S. Hu;* The Future of Real-time Cardiac Magnetic Resonance Imaging

[7] Mark Doyle, Edward G. Walsh, Gerald G. Blackwell, Gerald M. Pohost; Block Regional Interpolation Scheme for k-Space (BRISK): A Rapid Cardiac Imaging Technique; Magnetic Resonance in Medicine Volume 33, Issue 2, Date: February 1995, Pages: 163-170

[8] Jia-Hong Gao, Jinhu Xiong, Song Lai, E. Mark Haacke, Marty G. Woldorff, Jinqi Li, Peter T. Fox; Improving the temporal resolution of functional MR imaging using keyhole techniques; Magnetic Resonance in Medicine Volume 35, Issue 6, Date: June 1996, Pages: 854-860