Module 5: Dynamic Imaging and Phase Sharing

(true-FISP, TRICKS, CAPR, DISTAL, DISCO, HYPR)

• Review
• Improving Temporal Resolution
• True-FISP (I)
• True-FISP (II)
• Keyhole Imaging
• View sharing limitations
• TRICKS
• CAPR
• DISCO
• Radial Under sampling
• VIPR
• Constrained Reconstruction
• Compressed Sensing
• Applications
• Summary
Review

In Module 4, fractional sampling of k-space was discussed. By sampling less data, the imaging time can be reduced. As long as the centre of k-space, which contains most of the signal, is sampled sufficiently, reasonable image quality can be obtained. Fractional k-space collection can improve image quality for single shot methods, or reduce echo times.

In Module 3 radial methods were discussed. They are inherently inefficient, in that they need to be over-sampled in the radial direction (π/2 more points) than would be required for a Cartesian phase encoding method that sampled k-space on a grid. However, because these methods sample the centre of k-space with each line, under sampling the data has less potential issues.

This module will discuss under-sampling in time and radial k-space to improve acquisition speeds.
Improving Temporal Resolution

Dynamic imaging requires a series of images to be rapidly acquired, usually to follow a contrast bolus or multi-phase movement (e.g. cine imaging of the heart).

**Figure 5.1:** Several images often need to be acquired over time to follow a dynamic change. The temporal resolution is the time, $\Delta t$, between one image volume and the next.

In order to achieve good temporal resolution, often spatial resolution is sacrificed. A high spatial resolution requires more time which increases the time between images.

**Figure 5.2:** An example of the dynamic washout curve of contrast in breast tissue, with measurements taken at each circle. The dotted line is the real washout curve and the pink line shows how that is being modelled, depending upon the temporal resolution. The lower the temporal resolution, the less accurate it is. Scenario a) has a slow temporal resolution because of the time necessary to acquire the high spatial resolution. Scenario b) has a faster temporal resolution but lower spatial resolution.
True-FISP (I)

Dynamic multi-phase imaging in the body is largely performed with true-FISP (true Fast Imaging with Steady state Precession). Conventional sequences have spoiler or crusher gradients to remove the remaining steady state magnetisation at the end of the TR. Steady state methods use this remaining magnetisation and add it to the signal from the new excitation pulse. (See 7004 module 7)

The flip angle and timing in true-FISP are such that the echo is weighted towards a FID/GE mixture. The readout gradient is such that the total positive readout is balanced with negative lobes, to make sure the transverse magnetisation from previous excitations is properly refocussed.

Figure 5.3: The steady state condition of true-FISP, with balanced refocusing readout gradient.
True FISP (II)

There is a high degree of gradient switching in short TR period, which gives similar issues to that of EPI - additional chance of PNS and some noise. The contrast in a true-FISP image is the ratio $T_2^*/T_1$, which provides good blood-muscle contrast. The images can be prone to a banding artefact, where cancellation has occurred.

The extremely short TRs mean the images can be acquired very quickly. For example, the entire abdomen can be imaged in a single breath hold, and the blood, bile and fat are bright. Reasonable resolution images of the heart can be acquired from diastole to systole phases in dynamic or cine cardiac imaging in minutes, although they are usually limited to a small number of slices. EPI can be used in the same way and is actually a faster sequence, allowing more frames per heart-beat, but true-FISP has the better image quality. As the $T_2$ is shorter in the body than the head, the EPI images suffer increased distortions and the contrast between blood and myocardium is not as good. (See 7016 for more information on cardiac imaging).

Figure 5.4: Axial slice through the heart with True-FISP showing left and right ventricles.
Keyhole imaging

Keyhole imaging is a method used to achieve better temporal resolution without sacrificing spatial resolution. This family of methods, sometimes also referred to a view sharing, is normally used for dynamic imaging with contrast.

The centre of k-space or low-frequency information is sampled more frequently in time than the outer edges or high-frequency information. The high-frequency information is mostly noise and edge information which doesn't change extensively over time, and doesn't have to be sampled with the same temporal resolution. The central portion of k-space will give the signal change due to the contrast passage, and takes less time to acquire than the full resolution. The edge information from different time points can be combined with the central portion to obtain the same spatial resolution.

Figure 5.5: The full spatial resolution is only sampled occasionally, but the central portion is sampled at each time point. The high frequency information from time point 1 for example, can be combined with the central portion acquired at time point 2, and reconstructed as the full spatial resolution.
View sharing limitations

These view-sharing methods do have some limitations. They require special reconstruction algorithms. If there is patient motion from one time point to the next, then you can get blurring within the image. Contrast enhancement of structural edges can be obscured as the edge information is not as accurate as doing a full acquisition at each time point.

This can be seen in Figure 5.6, where it compares the acquisition of a central portion only with zero filling of the outside edge of k-space (5.6a), view sharing using the outer edge of k-space from before the contrast injection, and central portion post contrast arrival (5.6b), and a full resolution image (5.6c). The contrast enhancement is indicated by the arrow.

Figure 5.6: Comparison of different methods to achieve a reasonable temporal resolution in dynamic contrast imaging in the breast. a) Centre part of k-space only is acquired and the rest is zero filled, b) central part of k-space is obtained at this time point, but the image is reconstructed with the edge information acquired before contrast injection, and c) all of k-space is acquired at this time point. The edge of the enhancement is blurred in all but image c.
TRICKS

There are many different approaches to view sharing or keyhole imaging. One of these is TRICKS (Time Resolved Imaging of Contrast Kinetics). Different sections of k-space are sampled with different temporal frequencies. The full spatial resolution is broken into 4 segments (A,B,C,D), with each segment taking the same amount of time to acquire (see Figure 5.7).

Figure 5.7

The segments are combined to create different full resolution phases or views, see Animation 5.1.

Animation 5.1: Different segments of k-space are acquired over time. Press the “Set” buttons in order to see how they are combined to form full resolution images.
CAPR (Cartesian Acquisition with PR-like sampling) is another view sharing method. In this sequence, there is elliptical sampling of the centre of k-space, combined with projection reconstruction in wedges of the outer edges of k-space (see Module 3 for other projection methods). A pure radial technique does not have a problem with undersampling artifacts, but it can be inefficient with repeated sampling of the centre of k-space. Replacing the central sampling with an elliptical centric method improves the efficiency.

**Figure 5.8:** k-space sampling in the k_y-k_z plane for CAPR. The central section is fully sampled, but the outer radial sections are undersampled.

**Animation 5.2:** CAPR images are made up from different combinations of the sampled data. Press the "Set" buttons in order to see how the images develop over time.

Before reconstruction, any missing data between the outer wedges, or at the very corners are zero-filled. The angular width of the outer wedges can be altered, which changes the amount of undersampling.

**REFERENCE:** Madhuranthakam et. al., Magnetic Resonance in Medicine, 55:50-58, 2006
DISCO

DISCO stands for Differential Sub-sampling with Cartesian Ordering, and is another 3D sequence that allows for high temporal and spatial resolution.

The $k_y$-$k_z$ sampling in k-space is divided into N annular rings. Each ring is sub-sampled radially by a variable factor. The central portion is sampled fully each time, and the outer regions are progressively sub-sampled. In the outer rings, the sampling is done in a pseudo-randomised fashion, such that the whole area is covered by the time the different samplings are combined. This type of sampling leads to dispersed or incoherent ghosting. That is, the artefacts are weaker and often disappear compared to other keyhole methods (see Reference for an example).

Figure 5.9: DISCO sampling in $k_y$-$k_z$ with two annular rings: one central and one at the edge of k-space.

Animation 5.3: In DISCO, the central portion is sampled with greater frequency than the random filling of the outer ring. Press the "Set" buttons in order to see how the k-space information is combined.

Radial Under sampling

View sharing techniques such as those described above, do have a drawback in that there is some temporal blurring. If the whole of k-space could be covered at each time point, this would improve. Parallel imaging (discussed in Module 6) can help with accelerating acquisitions, or the image could be undersampled.

Cartesian methods must sample at the Nyquist rate or be subject to artefacts. A radial sequence, which samples the central portion of k-space with a greater density than the outer portions, and at each acquisition, can be undersampled. VIPR (vastly undersampled isotropic projection reconstruction) is one such method.
VIPR

VIPR performs a 3D projection trajectory, sampling the centre of k-space each with each projection. The projections are equally separated to sample the surface of a sphere. The acquisition order is interleaved so that orientations throughout the sphere are covered at a given frequency.

The artefacts from undersampling resemble noise rather than streaks, but if the number of projections is too low, it will become susceptible to streak artefacts. The data is regridded to a Cartesian plane and weighted by the radius at which it was acquired, with no zero-filling. VIPR is sensitive to off-resonance errors and trajectories not passing directly through the centre of k-space. Corrections can be applied for both of these during reconstruction to improve the image quality. It can suffer from a lack of SNR, proportional to the degree of undersampling.

Phase contrast VIPR has been used to obtain non-contrast-enhanced angiography, without the need for contrast injections.

![Figure 5.10](image.png)

**Figure 5.10:** Illustration of the application of PC VIPR in a two month-old child with an aortic coarctation. The acquisition was respiratory-gated with free breathing and no contrast material. Increased flow velocity is indicated in red on the left. From: Mistretta, *JMRI* 2009.
Constrained Reconstruction

Constrained reconstruction can be applied to remove the issues with radial undersampling. A training image is used, that provides structural information, high SNR and few artefacts. This is used to constrain the reconstruction of the highly undersampled time frames with the temporal information.

HYPR, or highly constrained back projection, uses this technique. A composite image is formed by summing some or all of time frames acquired with interleaved radial or projection acquisitions. At each specific time frame, a weighted image is formed by combining the filtered back projection of the time frame projections with the resampled composite image. The weighted image emphasises which components of the composite image are within the time frame. When the weighted and composite are multiplied together, it will result in a high SNR image for the time frame, with reduced streak artefacts.

**Figure 5.11:** HYPR process. Undersampled radial images are acquired with interleaved projection angles and reconstructed with conventional filtered back projection (FBP). These images are summed to form a composite image. A weighted image is created from the FBP at each time point plus the composite image resampled to the same projection angles as the time frame. The full composite image is multiplied by the weighted image to obtain the artefact free HYPR image. Based on image from Mistretta, *JMRI*, 29:510-516, 2009
Compressed Sensing

Compressed sensing aims to reconstruct images at full resolution from a smaller sample of measurements than are normally acquired. For successful application of the following criteria must be met.

1. Must be sparse in one of the transform domains. For example, it could be in the pixel domain, such as CE angiograms that have small areas of signal (blood vessels) but are mostly void. Otherwise it could be in the spatial domain where the gradient field is sparse, or in the temporal dimension for dynamic imaging.

2. Aliasing artefacts caused by undersampling must be incoherent (noise like). This can be achieved by sampling the signal in a pseudo-random pattern (See Figure 5.12). The slice encoding direction in 3D Cartesian sequences have reduced coherence, and incoherent noise can be found in radial, variable density spiral or variable density Cartesian acquisitions.

![Figure 5.12: Example of compressed sensing pseudo-random sampling compared to linear sampling](image)

3. Reconstruction is done with a non-linear method. The algorithms do iterative thresholding and interference cancellation.
Figure 5.13: Top line: 3D contrast enhanced angiography using a) Nyquist sampling, b) low-resolution centric k-space sampling, c) linear reconstruction of the random undersampling, and d) compressed sensing with non-linear reconstruction of the random undersampling. Bottom line: the 3D Cartesian random 10-fold undersampled configuration.
http://www.stanford.edu/~mlustig/CSMRI.pdf
Applications

These set of keyhole imaging sequences are specifically used for contrast enhanced angiography or dynamic susceptibility imaging, where a contrast bolus is injected and followed over time. The benefit of the quicker temporal resolution means CE-MRA without venous contamination. With improved spatial resolution, the smaller vessels in the peripheral vasculature are easier to investigate.

**Figure 5.14:** a) VIPR image of the abdominal vasculature showing maximal arterial concentration and large field of view (Barger, MRM, 2002); b) CAPR of carotid arteries (sagittal right side view) with resolution of smaller vessels shown by arrows (Madhuranthakam, *MRM*, 2006)

For more information on vascular imaging, see MRES7006.

DISCO was specifically designed for abdominal imaging, and can be combined with Dixon-based fat-water separation. Because it offers 3-4 times temporal improvement over other methods like VIBE, it can accurately capture rapid arterial phase enhancement in areas like the liver.
Figure 5.15: 53 yo female with likely heptocellular carcinoma. The hyper-enhancement of the tumor only appears in the early phases (inferior to 8s post contrast).
Summary

This module has focused on methods to increase temporal resolution or image acquisition

- Imaging with short TR as in true-FISP

- view sharing over time (sampling the centre of k-space more often than the edges)

- undersampling radial images

- undersampling plus constrained linear reconstruction to remove artefacts

- undersampling plus compressed sensing non-linear reconstruction to remove artefacts

Some of the methods mentioned above are complimentary and can be combined together to further decrease the image acquisition time. For example compressed sensing and constrained reconstruction both work well with undersampled radial images. They can also be combined with features mentioned in previous modules to produce an even faster hybrid technique, e.g. compressed sensing and conjugate symmetry.

Review Questions

What features do you need to perform dynamic imaging in the body?

How does True-FISP work? What are its advantages and disadvantages?

What is view sharing/keyhole imaging? How does it work? What are the general advantages and disadvantages?

How do TRICKS, CAPR and DISCO work? What are their advantages and disadvantages? When would you use one technique over another?

Why can RADIAL be vastly under sampled? What advantages and disadvantages does VIPR have?

How can constrained reconstruction be used to improve vastly under sampled images?

What is compressed sensing? How does it work and when would you use it?

What applications do these dynamic imaging sequences suit and why?