Nuclear diagnostics and Magnetic Resonance Imaging

Lecture 12: Magnetic Resonance Imaging: artefacts

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Outline

1. **Artefacts in Magnetic Resonance Imaging**
   - Introduction
   - Aliasing (wraparound) and the Nyquist theorem
   - Truncation artefact; Gibbs phenomenon
   - Random motion artefacts

2. **Lecture summary**

Section 1

Artefacts in Magnetic Resonance Imaging

Artefacts in MRI

Ghosting due to total internal reflection of bright sources in optical photography

Just as in optical photography, artefacts are unwanted image features

Artefacts arise from many causes:

- Field imperfections (not addressed below)
- Movement of patient or organ
- Magnetic material (e.g. from bone repairs)
- Chemical composition uncertainties

My objective is to give examples, there is an extensive literature on the subject

Reconstruction of the MR image; reprise

Gradient pulses G_i are used to allow slice-selective excitation and to allow spatial information to be encoded into the net magnetisation:

$$B_z(x, y, z, t) = B_0 + xG_x(t) + yG_y(t) + zG_z(t)$$

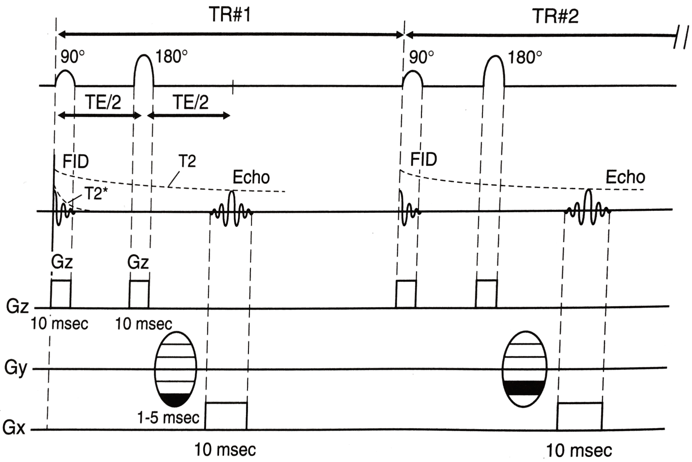
Spatial information is encoded into net magnetisation in k-space, often:

- Frequency encoding is used to encode features in the x direction
- Phase encoding is used to encode features in the y direction

2D Fourier transform used to transform image in k space to image in coordinate space

Pulse sequence is repeated to collect data for all $N_x \times N_y$ pixels of image

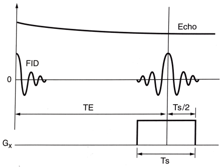
Spin-echo sequence; reprise



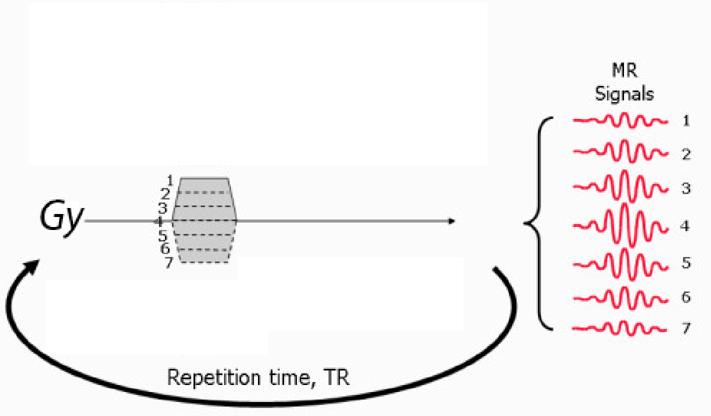
Readout occurs when frequency-encoding pulse (G_x) is on (T_S, the sampling time)

Each repetition corresponds to a new G_y, i.e. a new encoding of phase

Take N_y repetitions to fill N_y rows in the image



Phase encoding; reprise (1 of 3)

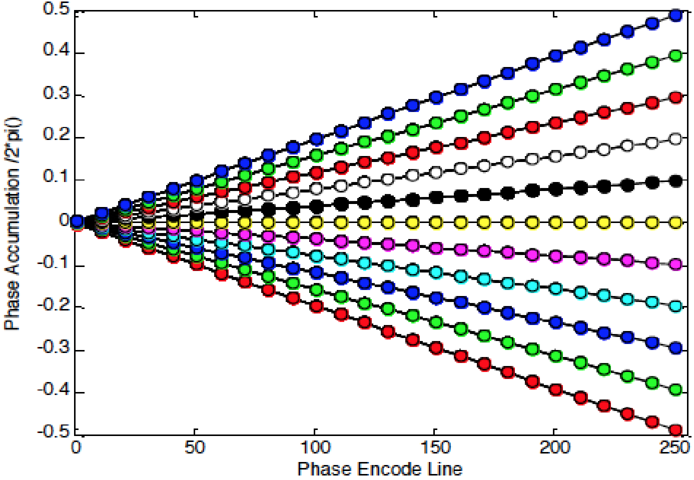


Central line in k-space will contain phase-encoding step with weakest gradient and strongest signal

Periphery of k-space sill contain phase-encoding steps with the strongest gradients and weakest signal

Each slice "has its own k-space because excitation is tuned to G_z

Phase encoding; reprise (2 of 3)



Phase wrt $y = 0$ accumulates with time, t, while phase-encoding gradient, G_y, is on:

$$\Phi(G_y, y, t) = (\gamma G_y)\, yt \qquad (1)$$

The slope of the line in the figure is determined by y

I.e. the rate of change of phase (frequency) is given by:

$$\frac{\Delta\Phi}{\Delta t} = (\gamma G_y)\, y$$

2D Fourier transform revisited

If the phase-encoding pulse is of length τ_{pe}, then the change of phase of the spins relative to $y = 0$ at the end of the pulse will be given by:

$$\frac{\Delta\Phi}{\Delta y} = (\gamma G_y \tau_{pe})$$

Lets take the start of the frequency-encoding pulse, G_x, to be at $t = 0$, then, the phase advance of ^{1}H nuclei at x after time t will be:

$$\phi(G_x, x, t) = (\gamma G_x)xt \qquad \text{i.e.} \qquad \frac{\Delta\phi}{\Delta x} = (\gamma G_x)t$$

As in lecture 10, let $\rho(x, y)$ be the intensity pixel-by-pixel in coordinate space, then the signal S will be given by:

$$S\left(G_y, \tau_{pe}, G_x, t\right) = \int_{y_{\min}}^{y_{\max}} \int_{x_{\min}}^{x_{\max}} \rho\left(x, y\right) \exp\left[-i\left(\gamma G_x t\right) x\right] \exp\left[-i\left(\gamma G_y \tau_{pe}\right) y\right] dxdy$$

2D Fourier transform revisited

In lecture 10, 2D Fourier transform from coordinate to k space was given as:

$$S\left(k_x, k_y\right) = \int_{y_{\min}}^{y_{\max}} \int_{x_{\min}}^{x_{\max}} \rho\left(x, y\right) \exp\left(-i2\pi k_x x\right) \exp\left(-i2\pi k_y y\right) dxdy$$

where $S(k_x, k_y)$ is the intensity pixel-by-pixel in k space

If we identify:

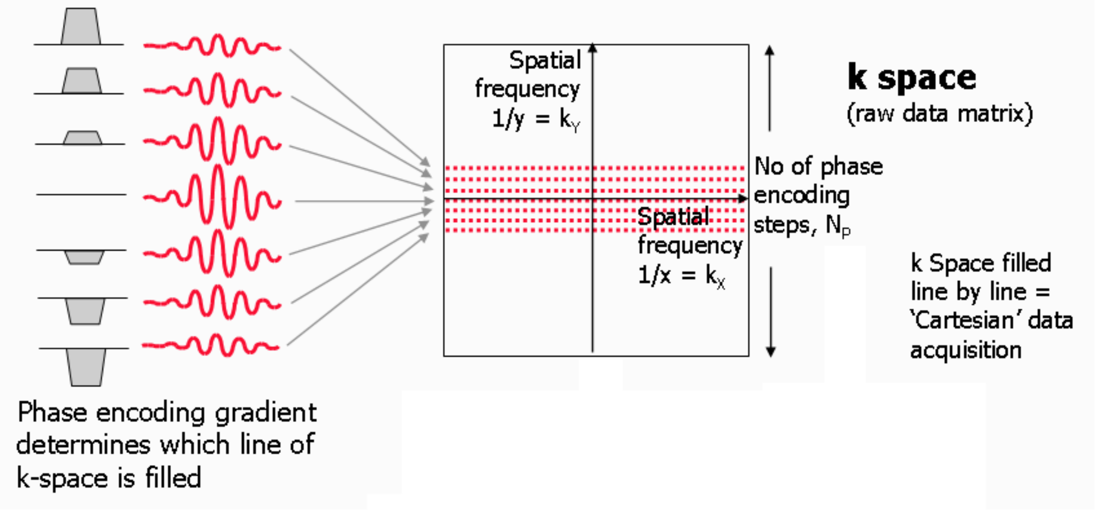
$$\begin{aligned} k_x &= \frac{\gamma}{2\pi} G_x t \\ k_y &= \frac{\gamma}{2\pi} G_y \tau_{pe} \end{aligned}$$

then:

$$S\left(k_x, k_y\right) = S\left(G_y, \tau_{pe}, G_x, t\right)$$

And the measured signal, S, is the k-space representation of the coordinate-space intensity ρ

Phase encoding; reprise (3 of 3)



In summary

The slice is selected by tuning the RF frequency and G_z

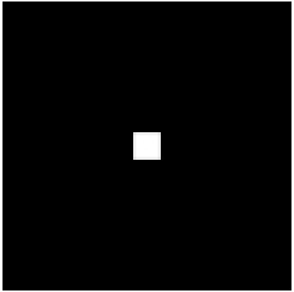
The k_x coordinate is obtained from frequency encoding **at readout**

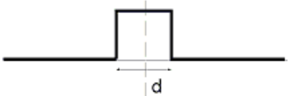
The k_y coordinate is obtained from phase encoding **"passively" by manipulating phase during free induction decay (FID)**

Trial: square centred at $(x, y) = (0, 0)$

Consider spatial encoding, x, direction

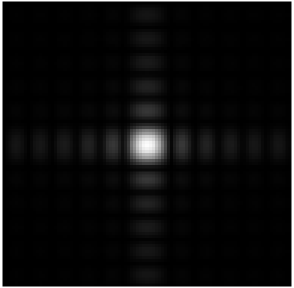
Coordinate space

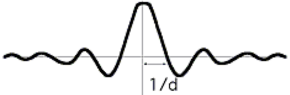




$$S(x) = \begin{cases} S_0 & \text{for } -\frac{d}{2} < x < \frac{d}{2} \\ 0 & \text{otherwise} \end{cases}$$

k space





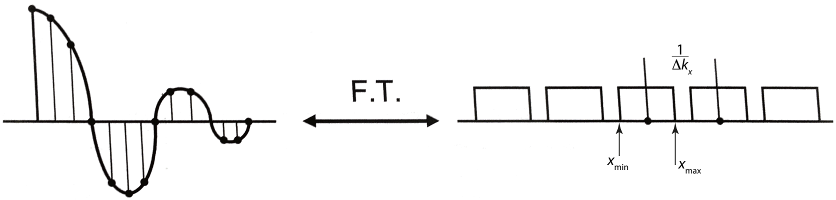
$$S(\Delta k_x) = S_0' \mathrm{sinc}(\Delta k_x)$$

Sampling of the signal recorded along k_x

The Fourier transform of "sinc" function will give "box" function if all Δk_x are sampled

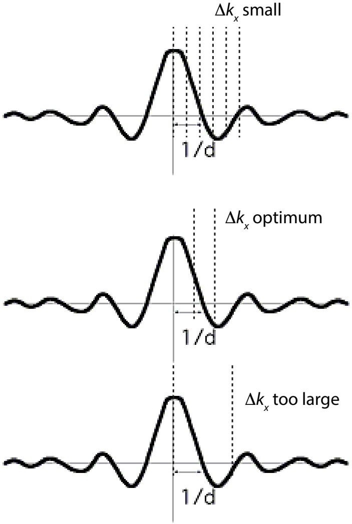
But, sinc function is only sampled at intervals of Δk_x

This means that Fourier transform of the sampled sinc function generates a series of (distorted) images of the box:



Sequence truncated at field of view

Sampling of the signal recorded along k_x



Nyquist theorem:
To reconstruct a bandwidth limited signal, require to sample the highest frequency that the signal contains at least twice

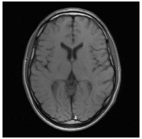
In our case, the bandwidth is limited by the truncation of the sinc function by the field of view in k space

At limit of resolution, box functions are "just separated"

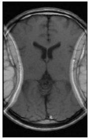
If sampling rate is too low, $\Delta k_x > \frac{2}{2\pi(x_{\max} - x_{min}})$, the boxes overlap and aliasing occurs

Aliasing

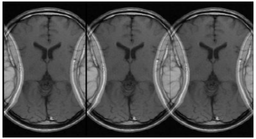
Image of head with appropriate sampling rate (field of view)



Truncated field of view yields sampling rate that is too low . . .

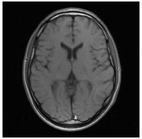


. . . and leads to aliasing

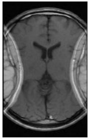


Aliasing (wraparound)

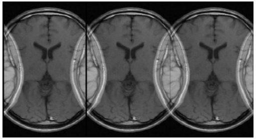
Image of head with appropriate sampling rate (field of view)



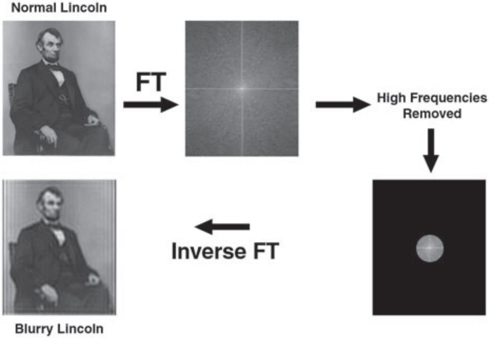
Truncated field of view yields sampling rate that is too low . . .

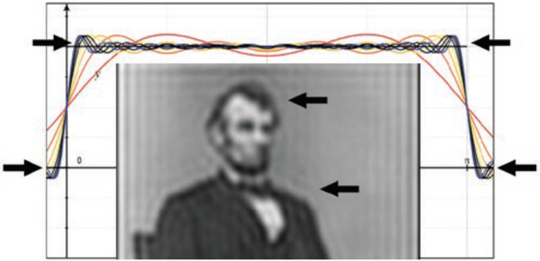


. . . and leads to aliasing



Effect of truncation in k space

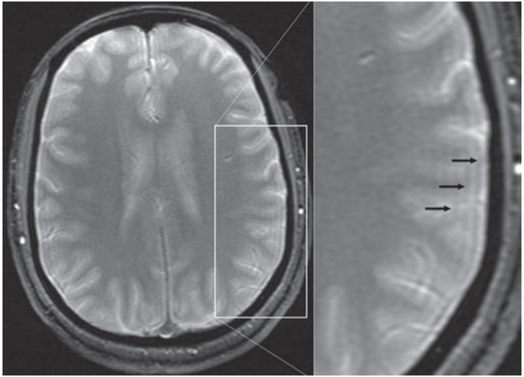




The Gibbs phenomenon

Artefact occurs at interfaces between tissues which have a rapid change in signal . . . "high contrast interfaces"

E.g. skull to brain



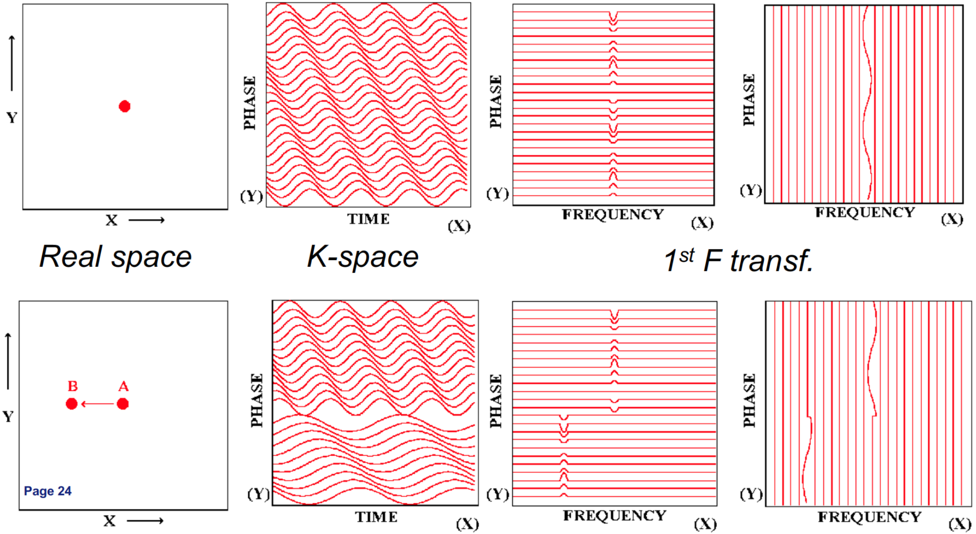
Motion artefacts; general comments

Motion artefacts most commonly observed in the phase-encoding direction

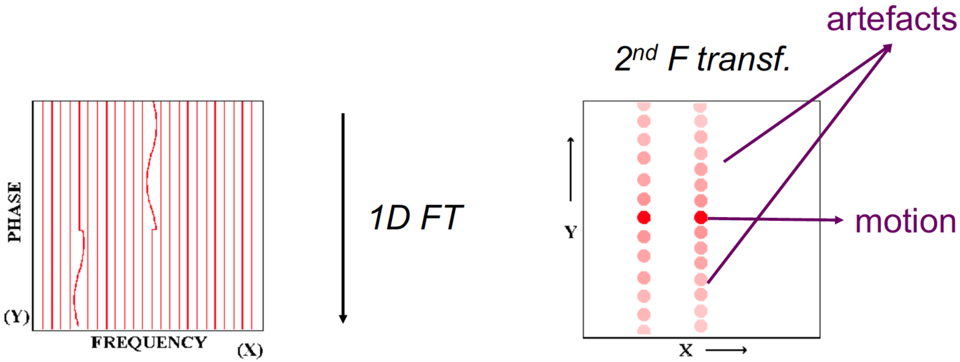
This is because:

- Motion along any field gradient results in the abnormal integration of phase, which is then incorrectly mapped onto the phase-encoding direction
- Frequency encoding is performed while G_x gradient pulse is on; typically for around 10 ms. Only very modest displacements can occur in such a short time. The result is that random displacements in the frequency-encoding direction lead to blur
- By contrast, displacements due to motion can build up between phase-encoding pulses, G_y, as these occur at intervals of TR . . . and TR can range from, e.g. 500 ms to a second or so

Example: displacement along x

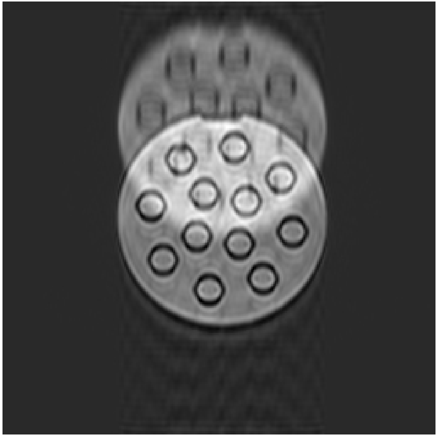


Example: displacement along x – continued



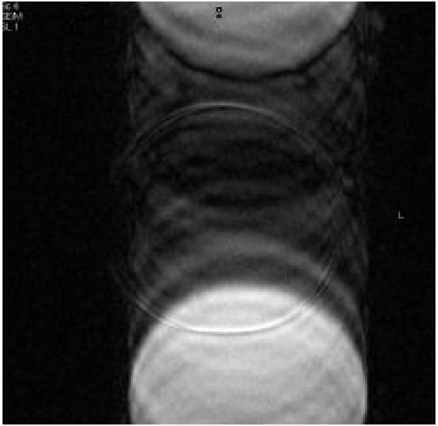
Displacement artefacts: questions 1

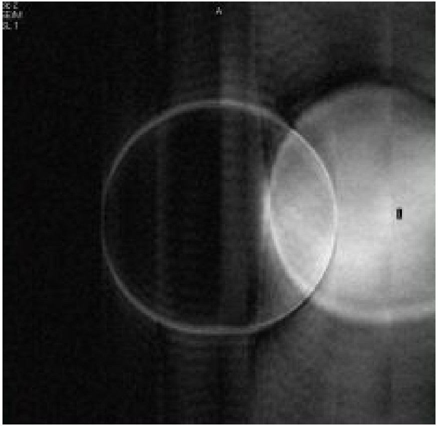
What causes the artefacts seen in the following images?



Displacement artefacts: questions 2

What causes the artefacts seen in the following images?





Section 2

Lecture summary

Summary

Spatial encoding, key facts:

- The slice is selected by tuning the RF frequency and G_z
- The k_x coordinate is obtained from frequency encoding **at readout**
- The k_y coordinate is obtained from phase encoding **"passively" by manipulating phase during free induction decay (FID)**

Aliasing (wraparound) artefact:

- Related to limited field of view;
- Spatial frequencies $k_i < k_{i\,\mathrm{min}}$ or $k_i > k_{i\,\mathrm{max}}$ wraparound and appear at $k_{i\,\mathrm{max}} - k_i$ or $k_{i\,\mathrm{min}} + k_i$ respectively

Summary

Gibbs artefact (truncation artefact): removal of high k_i leading to:

- Loss of definition at edges of features;
- Striations in the neighbourhood of edges at which there is a large step in brightness

Random motion artefacts:

- Most often occur in the phase-encoding direction;
- Often associated with ghosting in the phase-encoding direction