

IMAGE PROCESSING IN MR
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The object of the lecture is to provide an introduction to and understanding of the following topics

1. Properties of MRI images and the raw data from which they are produced.
2. Image processing as part of image formation.
3. Pre-processing in the image domain.
4. Parameter images
5. Segmentation and measurement
6. Use of parallel data streams from array capable scanners
7. Time course imaging.

Introduction

1. Focus on MR Images (and Spectra).

- A wide range of generic image processing tools can be applied (see notes for other lectures).
- Specific properties of MR data are important in choosing methods and in generating problems to be solved.

2. MR data properties

Spatial encoding is generally achieved using gradient magnetic fields to impose linear spatial variations in the resonant (Lamor) frequency (ν in radians/second).

$$\omega = \gamma(B_0 + \underline{G} \cdot \underline{r})$$

where γ is the gyromagnetic ratio (in radians/second per Tesla of applied magnetic field) of the nucleus being detected, B_0 is the magnitude of the main magnetic field of the MR scanner (assumed to be spatially homogenous), \underline{r} (in meters) is a position vector of a point in space and \underline{G} is an applied magnetic field gradient (in Tesla/meters) which may be time varying both in amplitude and direction.

After demodulation, which shifts the frequency by γB_0 , the signal (s , arbitrary units) received at a time t (seconds) after excitation is

$$s(t) = \int_{\text{object}} A B(\underline{r}; T_1, T_2, D \dots) \exp\left\{-i \int_0^t \underline{g} \underline{G}(t') \cdot \underline{r} dt'\right\} \rho(\underline{r}) d\underline{r}$$

where A is a sensitivity constant representing instrumental factors, B is the effect on the signal at time t of various parameters such as the time constants T_1 and T_2 , the diffusion coefficient D , i is the square root of -1 , the exponential term represents the accumulated phase of the signal from location \underline{r} and $\rho(\underline{r})$ is

the signal from an elemental volume at \underline{r} . Replacing $\int_0^t \underline{g} \underline{G}(t') dt'$ by \underline{k} gives

$$s(\underline{k}(t)) = A \int_{\text{object}} B(\underline{r}, t; T_1, T_2, D \dots) \rho(\underline{r}) \exp\{-i \underline{k} \cdot \underline{r}\} d\underline{r}$$

An MR image, which is a spatial map of $B \cdot \rho(\underline{r})$, can be produced by Fourier Transform (FT) of s . Image data acquisition is achieved by appropriately sampling $s(\underline{k})$. To obtain sufficient data to produce an image $s(\underline{k})$ must be sampled at appropriate values of \underline{k} . For a simple two-dimensional slice in the (x, y) plane, $\underline{k} = (k_x, k_y)$ and discrete samples of s must be obtained at

increments of $\Delta k_x = \frac{2\pi}{\Delta x}$, $\Delta k_y = \frac{2\pi}{\Delta y}$ up to maximum values of $k_x^{\text{max}} = \frac{2\pi}{\Delta x}$ and

$k_y^{\max} = \frac{2p}{dy}$, where $(\Delta x, \Delta y)$ are the limits of the desired field of view of the

image and $(\delta x, \delta y)$ set the required spatial resolutions in x and y. In most conventional acquisition strategies, one line of \underline{k} space is acquired each time the nuclear magnetism is excited and a cyclical excitation pattern is used to build up a full dataset. With this scheme the gradient applied during readout (e.g. to sample a full range of $k_x(t)$) is called the frequency encode or read gradient and each distinct line of \underline{k} space is achieved by briefly applying an orthogonal gradient called the phase encode gradient which introduces the necessary incremental steps in k_y .

Spectroscopy data can be spatially localised using methods similar to those used in imaging, but data collection is performed in the absence of applied gradients so that the spectral content of the data reflects the chemical environment of the contributing spins.

To summarise; the raw data for MR images is acquired in reciprocal, or \underline{k} , space. Most current techniques employ a raster scan of \underline{k} space in which data is acquired on a uniformly spaced rectangular grid. Such \underline{k} space data may be transformed to form images by FT using discrete or fast FT (FFT). Direct optical Fourier transform systems have also been demonstrated. Non-uniformly sampled k-space data generally requires transforming to a uniform grid (so called re-gridding) if FT methods are to be used for image production. Alternative image formation algorithms include back projection of radial lines in k-space, wavelet transformations and Hadamad encoding. However, almost all images are currently produced by Fourier methods from uniformly sampled or re-gridded data. In general, a limited region of \underline{k} space is sampled and this results in strictly band limited data so that the point spread function in the final image is a sinc function. Both the \underline{k} space data and the image domain data are intrinsically complex quantities. However, for most applications magnitude (or modulus) images are produced. The phase of the image data may be useful for some applications, e.g. quantitative flow imaging or temperature measurement. For real objects, production of magnitude images does not change the spectral properties of the data except where there are negative pixels, such as on the dark side of edges of bright objects and in noise dominated regions. Forming magnitude images in the presence of such regions produces out of band aliasing and changes the noise statistics (see notes by RM Henkelman).

The signal properties of MR images depend on many parameters including the relaxation times T_1 and T_2 , spin density, susceptibility, diffusion, perfusion, bulk flow, temperature, etc. By changing scanning parameters such as the repetition time or by changing the scanning sequence it is possible to vary the selective weights with which these parameters influence the signal. Pure parameter maps may be produced by forming appropriate combinations of images acquired under different conditions.

Acquisition times for complete image data sets can be reduced by multi-echo techniques in which more than one line of k-space is encoded for each signal excitation. This can result in different parts of k-space having different signal

properties as a result of T_2 weighting and flow or motion effects. Multi-echo imaging is often generalised to non-linear k-space sampling trajectories, for example in spiral imaging.

Image artefacts are frequently non-localised in Fourier encoded MR images. Different k space acquisition strategies can have quite different modes of image degradation in the presence of motion or the system perturbation and this may have major implications for image processing strategies adopted.

In general, MR images are characterised by high contrast and high signal-to-noise ratio (SNR). However, for *in vivo* data the apparent noise frequently has substantial contributions from motion induced artefacts reducing the apparent SNR.

Both excitation and data collection can be expressed as Fourier processes, so that Fourier concepts and methods are central to both acquisition and data processing.

3. Image processing as part of image formation

Multi-echo imaging and novel k-space trajectories both present image processing challenges. Key steps relate to:

- i) Achieving consistent data across k-space in the presence of decay processes and off resonance effects.
 - Typical processing steps: data alignment, phase correction, amplitude correction.
- ii) Data regridding to achieve uniform sampling for FFT processing. Typical methods:
 - Detection of k-space offsets (e.g. from navigator echoes)
 - Convolution regridding.
- iii) Filling in of missing data in partial k-space acquisitions. Typical methods include:
 - Use of Hermitian symmetry and phase correction
 - Interpolation
 - Linear prediction methods such as SVD
- iv) Retrospective gating and re-ordering methods to achieve increased temporal resolution or reduce artefacts by:
 - Substitution of some k-space data (eg key hole methods)
 - Sliding a window over continuously updated k-space data.

- Reordering phase encodes to convert asynchronous subject movement into a smooth coordinated motion (e.g. for control of artefacts due to respiration)

4. Image domain correction/processing methods

i) Intensity correction for systems and coil performance (e.g. surface coil correction)

- Use of knowledge about coil sensitivity.
- Low pass filtering and other linear methods of coil sensitivity estimation from image data.
- Non-linear methods. e.g. exclusion of edge content in coil sensitivity estimation
- Histogram re-normalisation and parametric fitting

ii) Distortion correction

- Use of phantom data
- Use of reference images.
- Modelling methods, e.g. eddy current models in EPI.

iii) Phase unwrapping - This is usually a necessary step if phase information is required.

Methods include:

- Spatial differentiation to eliminate phase wrap artefacts.
- Region growing
- Model function fitting.

iv) Filters for noise reduction/image (or spectral) enhancement

- Wide range of image filtering used.

v) MR spectra may suffer from base line roll through loss of initial time points in the raw data. This can be corrected in the frequency domain (or in the time domain). A wide range of filters is used for MRS.

vi) There are also standard procedures such as multiplanar reformatting (MPR) and maximum intensity projection (MIP). The former is self explanatory, while the latter is used to visualise vessels in angiographic images.

5. Parameter map production.

Using the theoretical parameter dependencies of MR signals pure parameter maps can be produced.

- Simple methods include log-ratio of measured signals for calculating T_2 , or diffusion coefficients etc from pairs of images (two point methods).
- Least squares and other fitting methods for larger data sets.
- Knowledge based methods, e.g. non-negative least square methods for multi spectral analysis.
- Use of multiple measurements to produce eigen vector images or spectra of multi-parameter systems. eg Diffusion tensor imaging and perfusion imaging with separation of tracer transit time and CBV etc.
- Line shape fitting to enhance information extraction from spectra or MT dispersion data. [Knowledge base derived from *ex vivo* or *in vitro* data.]

5. Segmentation and Measurement.

- i) Wide range of "standard" segmentation methods applicable (see other lecture notes). Of special interest for MRI:
 - Multi-spectral methods based on combination of MR images with different contrasts; cluster analysis identifies tissue types in an appropriate multi-dimensional space.
 - Edge/surface detection combined with modelling is increasingly being used to produce simplified structures for virtual reality simulation (eg Virtual Colonoscopy) or to visualise complex motion (eg models of the beating heart).
- ii) Confidence testing (e.g. fMRI)

Methods borrowed from PET based on distinguishing signal (e.g. mean change) from noise by parametric and non-parametric tests or correlation analysis. Powerful provided the "noise" has appropriate properties: with MR images, the task is frequently to distinguish one signal from other signals or artefacts as well as noise.

6. Parallel data streams from array systems.

Many modern scanners have array coil capabilities in which complete, separate receive channels allow parallel data collection. Two complementary uses:

- i) SNR improvement by combination of channels to gain from coherent addition of signal against incoherent addition of noise.

- ii) Acquisition speed can be increased by exploiting spatial sensitivity of individual elements in arrays of coils to allow reduced Fourier/spatial encoding.
 - a) k-space method useful for specific coil geometries (eg a linear array), can synthesise missing k-space lines allowing reduction in number of lines acquired (SMASH)
 - b) Image domain method. Spatially distinct coils can separate mixed signals produced by spatial under sampling using knowledge of coil geometry and linear algorithms (SENSE).
 - c) Non-linear image domain methods. Optimisation methods can be used to help in untangling undersampled image data.

7. Time Course Imaging

This is an expanding area of application, particularly for dynamic contrast studies and fMRI. Key methods employ model fitting of time series (e.g. box car methods with periodic stimulus paradigms in fMRI). Interesting variations on the theme of time series analysis is to identify rapid change combined with under sampling strategies to explore relevant change with improved temporal resolution. (UNFOLD, ISMRM 1999, #90). A key methodology is image registration (see lecture notes by Hill and Hawkes) which is required to ensure that genuine change is not confused with changes in subject position over time.

8. Conclusion

These notes have focussed on MR specific processing methods and have omitted discussion of generic techniques as well as matters relating to image registration and artefact reduction, which have been dealt with by other speakers.

Image processing has wide application for MR data. An appreciation of the properties of MR acquisition leads to productive use of specially tailored methods, particularly for image production and extraction of specific physical parameters. Image processing methods are increasingly being integrated with image acquisition to produce powerful methods that reduce artefacts, speed up acquisition or increase data content or throughput.