How Modules of Imaging Sequences Fit Together: An Overview of Recent Advances in MR Imaging

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Abstract

The past decade has seen a vast number of new MRI sequences and a great deal of development of protocols, so that we are left with the question: Does the MRI terrain lend itself to complexity? The answer is no. MRI sequences are made of modules on image contrast and image acquisition. The purpose of this short reprise is to compile the well-established methods based on this modular approach together with recent advances in MRI. This will take away the mystery of seemingly complex MRI sequences.

An MRI sequence can be expressed as a series of time events. For instance, in conventional imaging, a Spin Echo sequence refers to a timed series comprising excitation – refocussing – readout and a Gradient Echo sequence refers to a timed series of excitation – dephasing – readout. These sequences are then repeated along the phase encoding direction. In a more generalised term this comprises the steps of excitation – phase encoding – frequency encoding. The image contrast relies mainly on TR and TE in a conventional sense.

Fast imaging is achieved through a transformation of this sequence. The sequence is now an ordered list of events: Preparation – evolution – detection, this initial idea dating back to 1990 by Haase et al. [1]. The first part of such a sequence prepares for image contrast whilst the second creates the contrast, and these evolve over time. This is followed by a detection part, which can yield the spatial resolution in one go, or even over a time course. In the last decade, ‘The many combinations of MRI’ [2] for structural and functional images rich in contrast have entered clinical routine. In this article, we attempt a classification of these MR techniques based on the concept of preparation – evolution – detection with the following subcategories of:

• Inversion Recovery prepared sequences
• Spin Echo / Gradient Echo prepared sequences
• Subtraction imaging
• Double preparation-evolution approaches

as shown in Table 1.

Contrast: Preparation – Evolution

The term ‘Preparation’ refers to preparation for T1, T2, and T2* contrast. ‘Evolution’ over time allows the spin system to change.

• T1 effects are achieved by inversion of the longitudinal magnetization, which can be in a non-selective manner, spatially-selective, or frequency-selective. The time to inversion recovery of T1 is used for nulling either lipid (STIR/SPAIR), CSF (FLAIR) or background signal in non-contrast MR angiography. Note that in the frequency-selective mode (SPAIR), only the signal-of-interest, e.g. lipid or silicone, follows this scheme of inversion recovery, hence leaving the water signal undisturbed for optimal signal-to-noise ratio. Other applications of TI effects include enhancement in contrast differentiation between grey matter and white matter (MPRAGE, MP2RAGE) or in-flow time in ASL.

• T2 contrast is generated by a Spin Echo preparation module. Its TE period can be used for T2 contrast preparation or encoding of diffusion (diffusion-weighted imaging).

• T2* weighting during a Gradient Echo sequence serves as a contact time for water in blood to exchange with deoxy- or meth-haemoglobin/hemosiderin deposits, to detect haemorrhagic lesions, or with oxy/deoxy-haemoglobin to produce BOLD contrast in fMRI, or to assess liver and cardiac iron overload.

• No contrast preparation: The FLASH sequence can produce PD/T1/T2*-weighted tissue contrast depending on the acquisition parameters, whilst TrueFISP exhibits an intrinsic T1/T2 contrast.
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Table 1 comprises MRI applications for neuro, cardiac, musculoskeletal, and body imaging with magnetization prepared contrast. The sequences are subdivided into modules of preparation – evolution – detection: The first expresses preparing for contrast, the second allows the magnetization to change, and the third performs the image. The modules under the detection part are in most instances interchangeable.
Imaging: Detection

Longitudinal or transverse magnetization?
A Gradient Echo or Spin Echo preparative module creates transverse magnetization. The read-out train in EPI directly uses this prepared transverse magnetization. However – unlike EPI – FLASH and TrueFISP are imaging techniques that require a separate excitation for each line of $k$-space. The prerequisite is the preparation of longitudinal magnetization. This is achieved using a 90° flip-back pulse at the end of the preparation – evolution period.

One-time contrast preparation
Even though the contrast preparation occurs at one time point, the contrast created decays and changes during the entire detection period, and is thus determined by the speed of readout and $k$-space traversal. In other words, the detection period should be of the same order of magnitude as the lifetime of the state of a magnetization-prepared contrast. Acquisition of the entire image after a single preparation-evolution period is primarily achieved by real-time imaging based on EPI or TrueFISP, followed by FLASH and HASTE, all providing ‘singleshot’ imaging but in the order of one-tenths to hundreds of milliseconds per image.

Repeated contrast preparation
When the lifetime (durability) of the state of a magnetization-prepared contrast does not match with a reasonable detection period, then segmentation in the phase dimension is required. In this scenario, multiple preparation-evolution periods are executed, one for each segmentation step. This is especially the case for TSE/SPACE as the acquisition time is relatively long, even for high turbo-factors. However, for each segmentation step, preparation – evolution – detection periods are separated in the same way as in the single-shot approach. The EPI sequence carries the additional option of segmentation in the readout dimension, which shortens the inter-echo time compared to shortening of the echo-train length for segmentation in the phase dimension. Otherwise, the concept of repeated contrast preparation is the same.

Repeated contrast preparation sequences are normally combined with methods for motion correction with either prospective acquisition correction PACE [25], or real-time correction using ECG and respiratory-
DTI-RESOLVE [26] (2A) Scheme of diffusion-weighted read-out segmented echo-planar imaging. The entire sequence of slice selective excitation-encoding of diffusion-sampling is repeated for each read-out segment. An illustrative example of the effect of read-out segmentation in reducing susceptibility artefacts is shown for the facial nerve: (2B) Axial T1-weighted image of the cisternal portion of the cranial nerves CN7 (arrow head) and CN8 (arrow). CN7 is exceedingly fine (~1 mm diameter) and in very close proximity (1-2 mm) to CN8. The cisternal portion of nerve is subject to distortion by CSF pulsation from the basilar artery. (2C) Tractography of the 7-8th CN complex using the syngo.via DTI software of four consecutive slices, based on nine read-out segments per image of 0.8 mm in-plane resolution. (3T MAGNETOM Skyra)

MP2RAGE of the midbrain. TR 5000 ms, TE 3 ms, TI 409 ms and 1100 ms; (3A) the shorter TI nulls white matter yielding superior contrast of substantia nigra, (3B) the longer TI provides grey matter / white matter contrast. (3T MAGNETOM Skyra)
Breathhold liver imaging with decreasing acquisition time (4A) T2 TSE (four breathholds of 19 seconds each with 10 seconds break: TA = 2:04 min), (4B) inversion-recovery HASTE (three breathholds of 23 seconds each with 8 seconds break: TA = 1:35 min), (4C) FLASH (one breathhold of 15 sec), and (4D) TrueFISP (one breathhold of 15 sec) of a tiny hepatic lesion in segment 7 compatible with a haemangioma (arrow). In comparing the image lesion conspicuity, TSE shows a high lesion-to-background contrast, and best lesional-liver contrast in HASTE but concomitant T2 blurring overestimating the lesion size. Note the sub-optimal predominantly T1-weighted contrast of lesion in FLASH, improved T2-weighting contrast on TrueFISP.

(1.5T MAGNETOM Aera)
gating. These methods allow data acquisition only if the patient’s position falls within an acceptance window i.e. the operator decides on the range of diaphragm positions or the stage of the cardiac cycle allowed in this window. For fast imaging of about 30 seconds or less, the image acquisition can be performed within a single breathhold window or in multiple breathhold windows if patients experience difficulties in maintaining even a short breathhold. Figure 4 is a pictorial of four different breathhold scans.

Conclusion
With the current status of the magnetic resonance technique, there is no general solution to fast imaging. Instead, this goal is achieved through various strategies, each well respected in its own niche. Preparation – evolution – detection is an expedient way of representing the versatile convertibility of imaging techniques.

Table 1 pulls together cornerstones of fast imaging strategies in achieving time-efficient acquisitions, each with its associated magnetization prepared contrast. Complementary combinations with different detection modules serve to avoid pitfalls and resolve artefacts in specific examinations. If, for example, the typical problems such as susceptibility-induced signal losses in EPI or sensitivity to off-resonance effects (balanced SSFP) compromise the quality of an image of interest, the appropriate module under the detection part can be readily changed while keeping the magnetization prepared contrast.

References
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