Pulse sequences in Cardiac MR

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Introduction

Cardiac MR imaging is performed through the application of fast imaging techniques synchronised with the ECG trace of the patient. The signal is sampled and encoded at a single or multiple time points within every heartbeat for a period of time in combination with breath holds to minimise the chest movements.
This text wants to provide a brief general overview of the pulse sequences implied in CMR and the two main types of acquisition: still imaging and cine imaging.

Key words

Still imaging, cine imaging, fast spin echo, fast gradient echo, spoiled GRE, bSSFP.

Main body pt.1

Still imaging mostly consists in the application of a fast spin echo pulse sequence in combination with a black blood double inversion preparation scheme.
“Still” means that the signal is sampled always at the same time point of the heartbeat for several heart beats until the k-space is filled. There is a trigger delay which is the time that goes from the R wave to the start of the sequence, it is chosen manually by the operator and depends on which cardiac phase the heart needs to be imaged in.

A spin echo pulse sequence is optimal for anatomical imaging because of its high signal to noise ratio: the 90° excitation pulse grants the maximum possible signal from the z-magnetization offered by the external field and the refocusing pulse rephases the spins and cancels the t2* effects. The weighting of the image contrast depends on the TR and TE chosen.
A conventional spin echo sequence has one refocusing pulse which goes to generate one echo within one TR, which means one phase encoding step – one sampling of the signal – one line of k-space filled.
A fast (or turbo) spin echo pulse sequence generates multiple refocusing pulses that give rise to multiple echoes which are encoded with different phase steps; thus more lines of k-space are filled within each TR (in CMR, being cardio synchronised, a TR is relative to the R-R interval with an average length of 1 R-R for T1 weighted SEs and 2 to 3 R-R for T2 weighted SEs).

The black blood preparation scheme is an optimization of the already intrinsic black blood contrast typical of SE sequences (washout effect) and it consists of 2 inversion pulses applied before the start of the FSE.
The first one is non-slice selective and is applied to the whole body area covered by the transmitter coil; it goes to invert the longitudinal magnetization of all the blood and tissues present in such area.
The second inversion pulse goes to reinvert the tissues withing the slice that is to be imaged by the FSE, bringing them back to the equilibrium value. Then, after a time TI (time of inversion) the 90° pulse is sent and the sequence starts.
The TI is the time that it takes for the inverted blood to reach the 0 point while "going back up" towards the equilibrium value due to T1 relaxation properties, and that is the time when the excitation pulse from the FSE doesn't provide any transversal magnetization (signal) from it, so that there is a "signal void" from the blood pool granting good contrast between the cavity and the walls of the heart or the vessel being imaged.

A black blood fast spin echo normally has an echo train length (ETL: number of echoes) of 15-20, which practically means that 1 or 2 slices can be acquired within one breathhold.

Main body pt.2

Cine imaging requires faster acquisition times and is practiced with gradient echo pulse sequences.

A gradient echo sequence generates the echo through the controlled application of magnetic field gradients. They are characterized by a typically very short TR which, being shorter than the relaxation times of the tissues, leaves a residual transversal magnetisation by the time the next RF pulse is applied. This residual signal can contribute or interfere with the signal generated by the following TR.
On the basis of this last point, the GRE sequences can be divided into two major groups: spoiled gradient echo sequences and balanced steady state free precession sequences (bSSFP).

The spoiled GREs get rid of the residual signal de-phasing it with the application of a spoiler gradient or with a technique called "RF spoiling".

The choice of flip angle, TR and TE determines if the picture is T1 or T2* weighted (the absence of a refocusing pulse doesn't allow the weighting in T2).

Spoiled GREs have an intrinsic bright blood contrast (inflow enhancement).

A flip angle smaller than 90° (usually 30°) works better with short TRs as a 90° pulse would transfer all the magnetization on the transversal plane but there wouldn't be enough time for the longitudinal recovery before the following RF pulse.
A small flip angle means that only a portion of the z-magnetization is used to generate the signal and there is more to use for the following TR.

The bSSFP sequences instead keep the residual signal, re-phasing it and carrying it over to the next TR where it adds up to the signal generated by the next RF pulse meaning in a much greater signal after a few TRs. A greater signal means that a wider receiver bandwidth can be used, meaning the TR can be shorter, meaning the imaging can be faster.

There is no conventional contrast weighting with the bSSFP GREs, the contrast is given by a T2/T1 ratio with characteristic high signal from the blood pool.

Cine imaging is the acquisition of the MR signal at multiple time points within the heart beat. An average R-R interval is calculated from the ECG trace which is used to determine how many cardiac phases can be acquired or retrospectively reconstructed. A different k-space is filled for each cardiac phase and after a number of heart beats a set of images is acquired that can be "played" in a cinematic sequence, allowing visual assessment of the cardiac motion.

The acquisition can be triggered or retrospectively gated.
When it's triggered it starts after a trigger delay right after the R wave and finishes right before the following one, waiting for the trigger of the next synchronisation pulse for the next acquisition. This method leaves a "blind spot" - a moment in the cardiac cycle that is not imaged - which can be a problem if the goal of the imaging is the assessment of diastolic or valve function.

The retrospective gated acquisition runs continuously and the data is assigned to the relative phases determined by the average R-R interval calculation after the k-space is filled.
The most common approach to cardiac cine imaging at 1.5T is to combine retrospective gating with a fast bSSFP GRE sequence.

Acceleration in GRE sequences is achieved by increasing the number of lines of k-space filled within a cardiac phase (shot). Increasing the acceleration factor decreases the imaging time (breath hold time) but increases the window of acquisition for each cardiac phase, lowering the temporal resolution resulting in a lower cine frame rate.

Conclusions

The 90° excitation pulse combined with the 180° refocusing pulse used by the spin echo give the largest possible signal provided the magnetisation is allowed to recover between repetitions.
Fast GRE sequences are used when imaging speed is more important than image quality. The absence of the refocusing pulse means loss of signal in the presence of magnetic susceptibility and at the boundaries between water and fat-based tissues.
Flowing blood looks different between the two techniques with the spin echo pulse sequences giving an intrinsic black blood appearance while the gradient echo pulse sequences giving a bright blood appearance.

References

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