A new flexible black-blood preparation sequence: reduced-angle double inversion recovery (RADIR)

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Introduction

Black blood imaging methods are widely used to observe myocardium and vessel walls and/or lumens. They suppress the magnetisation outside the imaging volume so that the signal from blood which subsequently flows into the imaging volume is suppressed. Two standard methods to achieve this are double inversion-recovery (DIR) [1] and the use of saturation bands above and below the imaging slice [2]. For DIR, blood suppression is usually good but it requires a relatively long delay time, until the inverted blood magnetisation crosses zero. Although this long delay time ensures the suppression even of very slowly flowing blood, it can be restrictive, e.g. it precludes the use of DIR during systolic heart phases, unless the acquisition is triggered from a previous heart-beat. By contrast, saturation bands can be used with much shorter delays but do not provide such effective blood suppression, partly because they saturate only a limited spatial region.

The new black-blood pulse sequence presented here allows suppression of all out-of-slice magnetisation, but allows the user the flexibility to choose shorter delay times for blood inflow than are needed for DIR, permitting applications at early cardiac phases.

Methods

To achieve signal nulling after time *TD*, the out-of-slice magnetisation must be rotated through an angle α ($90°<\alpha<180°$), while the imaging volume experiences zero net flip angle. The blood signal recovers by T1 relaxation, and crosses zero for image acquisition after *TD* if α is defined by: $\cos\alpha = \frac{\exp(-TD/T1)-1}{\exp(-TD/T1)-\exp(-TR/T1)}$. Depending on the inflow time for blood, *TD* could then be chosen to be any value between 0 (when α = 90°) and $TD_{\mathrm{DIR}} = T1.\ln\left(\frac{2}{1-\exp(-TR/T1)}\right)$, the inversion time used in DIR imaging (when α = 180°).

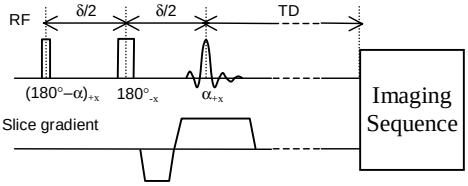

Figure 1: RADIR pulse sequence.

A pulse sequence that achieves this is shown in Figure 1. The non-selective 180° pulse refocusses the transverse magnetisation, preventing phase dispersion for off-resonance spins, which would cause image artefacts. When α=180°, the sequence becomes standard DIR (without adiabatic pulses).

An asymmetric RF pulse is used to reduce the $\delta/2$ time-periods, during which the transverse magnetisation component experiences T2 decay, without sacrificing slice profile sharpness. A typical value of δ was 7 ms. This could be further reduced by placing the refocusing lobe before the 180° pulse, but we avoided this since on our system image quality was slightly degraded by eddy currents.

This sequence was implemented on a 3T Intera scanner (Philips Medical Systems, Best, The Netherlands). The abdominal aortas of four healthy volunteers were scanned with a cardiac-triggered turbo-spin echo sequence (TE = 70ms, turbo factor 11) at various trigger-delay times. The SNR of blood from the proposed sequence was compared with results using DIR and out-of-slice presaturation.

Results

Figure 2 shows a comparison between DIR and RADIR that illustrates an advantage of the new method, namely that the systolic image can be triggered from the same heartbeat as the acquisition, giving improved consistency. The example in Figure 3 demonstrates that RADIR can give better blood suppression than presaturation.

When acquiring data from each heartbeat in 3 subjects, the average blood SNR, at trigger delay 450–470 ms, was 2.2 (RADIR), 2.6 (DIR) and 2.8 (presaturation). At trigger delay 300 ms (where DIR was not applicable) blood SNR was 1.6 (RADIR) and 1.9 (presaturation).

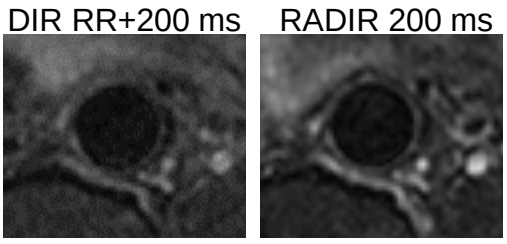

Figure 2: DIR and RADIR vessel wall images at trigger delay 200 ms after R-wave: to image in systole, DIR must be triggered from the previous heartbeat (TD_{DIR} = 630 ms, TD_{RADIR} = 100 ms).

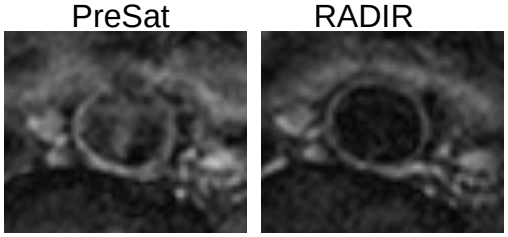

Figure 3: Images with out-of-slice presaturation and RADIR, trigger-delay 300 ms. Triggering was with PPU and TD_{RADIR} = 250 ms.

Discussion and Conclusions

Our previous studies in the abdominal aorta (results not shown) demonstrated that image quality varies significantly with cardiac trigger-delay, possibly due to motion effects. Therefore there may be benefits in choosing the trigger-delay time flexibly, without the restrictions imposed by a long DIR inversion time. Such a flexible choice could also benefit morphological black-blood cardiac imaging. The proposed sequence allows this greater flexibility, and achieves good blood suppression over much of the cardiac cycle. Unlike for presaturation bands, the out-of-slice suppression volume is not spatially limited, which can reduce or eliminate inflow-related artefacts in some cases.

In the case of very slow flow, the inflow time for the suppressed blood may be fairly long, and substantial reductions in *TD* are not appropriate in these cases. Further work will be required to determine appropriate values of *TD* for clinical applications in specific anatomical regions, depending on the flow-rates throughout the cardiac cycle.

An interesting possible application using longer *TD* values could be coronary vessel wall imaging at 3T. For *TR* of 2 heartbeats, TD_{DIR} can be too long to permit imaging in mid-diastolic diastasis in some subjects [3], while for *TR* of 1 heartbeat TD_{DIR} may be too short for reliable suppression.

Flip-angle inhomogeneities (occurring e.g. at high fields) will affect the quality of blood suppression using RADIR, as they do for non-adiabatic DIR; flip-angle mapping could allow RF power adaptations to reduce this effect. However, such RF inhomogeneities will not significantly affect the net flip angle in the imaging volume, since it is always zero when using the pulse phases indicated in Figure 1.

In addition to flexible sequence timing, potential advantages of short *TD* times include a reduced sensitivity to changes in *TR* (heart-rate variations), to T1 (after contrast agents) or to fast flow from outside the homogeneous volume of short-bore magnets. Additionally, α could be varied in real-time to compensate further for cardiac arrhythmia or heart-rate drifts, improving blood suppression for sequences with intrinsically bright blood signals. In future, RADIR could be combined with other DIR techniques, such as quadruple inversion recovery [4], local re-inversion for coronary wall imaging [5] or multi-slice DIR methods [6–8].

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References [1] Edelman RR et al. Radiology 1991;181:655–660. [2] Felmlee J et al. Radiology 1987;164:559–564. [3] Kim WY et al. J MRI 2001; 14: 383–90. [4] Yarnykh VL et al. Magn Reson Med 2002;48:899–905. [5] Botnar RM et al. Magn Reson Med 2001;46:848–54. [6] Song HK et al. Magn Reson Med 2002;47:616–20. [7] Parker DL et al. Magn Reson Med 2002;47:1017–21. [8] Mani V et al. Radiology 2004;232:281–8.