

**Novel Techniques of Magnetic Resonance  
Black-Blood Imaging Based on  
Motion-Sensitized Driven-Equilibrium (MSDE)**

**PhD dissertation**

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## **Chapter 1: Introduction**

Black-blood imaging is a unique magnetic resonance imaging (MRI) blood signal suppression technique. By suppressing blood signals, it visualizes targeted tissue pathological changes, such as carotid vessel wall atherosclerotic plaque or acute myocardial infarction, which exhibit high intensity without blood signal suppression. The double-inversion recovery (DIR) method is a widely used black-blood approach, because it generally provides excellent image contrast and signal-to-noise ratio. However, its use in the clinical setting is limited due to issues involving acquisition time or spatial coverage. One clue for breaking through these limitations is a recently proposed technique called motion-sensitized driven-equilibrium (MSDE).

The goal of the present research is to evocate the clinical usefulness of using MSDE including new applications, with foci on two technical issues: first, optimizing the MSDE pulse design itself to improve image quality; and second, based on the optimized MSDE design, optimizing entire sequence parameters or schemes to obtain appropriate images required for specific clinical applications.

## **Chapter 2: Double Inversion Recovery (DIR) Black-Blood Imaging**

The conventional approach for black-blood imaging hitherto is the DIR technique developed by Edelman and colleagues. It is a promising approach and widely used for various clinical applications as it can provide an excellent contrast-to-noise ratio (CNR) and a high signal-to-noise ratio (SNR) in the images. By combining DIR with multiple contrast turbo spin echo (TSE) based acquisitions, the morphology and tissue composition of atherosclerotic plaque can be assessed. Therefore, DIR-TSE black-blood imaging is widely used in atherosclerosis plaque imaging applications.

Limitations still exist, however, in the application of this technique. A major limitation is its anatomical coverage if achieving appropriate blood signal suppression within a clinically practical scan time. The slice or slab thickness affects the efficiency of the blood signal suppression, while the blood signal suppression mechanism itself limits the spatial

coverage. Indeed, DIR relies on the inflow of blood with its signal nulled through inversion recovery time into the imaging volume and the outflow of non-inverted blood from the volume. Therefore, the blood signal suppression efficiency decreases as the acquisition volume increases. In addition, for the same reason, the black-blood condition will be compromised if the imaging plane is not perpendicular to the flow direction, as the inflow and outflow effects weaken. Thus, imaging orientation is limited by the running direction of the targeted vessels. Furthermore, it also relies on the  $T_1$  value of the blood, as the timing for optimal blood suppression is  $T_1$  dependent; when contrast media is used, the efficacy of blood suppression will be impacted.

### **Chapter 3: Motion-Sensitized Driven-Equilibrium (MSDE) Black-Blood Imaging**

To overcome the problems of the DIR approach, the MSDE black-blood imaging technique was developed based on the use of motion-sensitized gradients (MSG) to dephase all moving blood spins prior to imaging. When combined with a fast acquisition technique, it can be used for imaging thick three-dimensional (3D) volumes or acquisitions of a plane including the targeted vessel running in parallel while maintaining blood signal suppression efficacy over a large volume.

### **Chapter 4: Comparison between Two Types of Improved Motion-Sensitized Driven-Equilibrium (iMSDE) for Intracranial Black-Blood Imaging at 3.0T**

MSDE provides several clinical benefits, including improved flow signal suppression effects, volume acquisition and wider anatomical coverage, or faster acquisition time as compared to the conventional DIR technique. The original MSDE, however, is known to be sensitive to the static magnetic field ( $B_0$ ) inhomogeneity, transmit magnetic field ( $B_1$ ) inhomogeneity and eddy currents effect, leading to image degradation.

The previously proposed iMSDE scheme adopted two Malcolm Levitt (MLEV)

designed refocusing pulses and two pairs of bipolar gradients designs. Computer simulation and phantom studies validated that iMSDE reduces eddy currents and  $B_1$  inhomogeneity effects compared to conventional MSDE. The clinical usefulness of iMSDE for carotid artery wall imaging has been confirmed at 3.0T.

Demanding wider clinical use, further optimization of iMSDE was conducted in the present research. This design is called iMSDE advanced or iMSDE-A in this thesis. The iMSDE-A technique was proposed to achieve further eddy current compensation from the iMSDE design by incorporating extra gradients in front of the preparation pulses. The computer simulations proved that the eddy current effect is compensated more effectively in the iMSDE-A design. This effectiveness was then validated in the corresponding in vivo studies demonstrating that a significantly higher signal intensity was obtained than from the original iMSDE technique. This finding suggests that the iMSDE-A design may extend the applicability of the technique to clinically important applications such as atherosclerosis, vasculitis, artery dissection, or metastasis screening in the intracranial region.

## **Chapter 5: Assessment of iMSDE-A for Multi-Contrast Vessel Wall Screening**

It is essential that plaque imaging procedures provide appropriate contrasts depicting plaque formulation and characterizations. In this chapter, a fast iMSDE-A design with 3D and multi-contrast features was proposed for carotid arterial vessel wall screening. The novelty of the sequence optimization is to balance the multi-contrast functionality with the high acquisition speed. In the comparison with the conventional DIR sequence, the iMSDE-A-combined optimized sequence was proven to provide similar tissue contrast in the  $T_1W$  and  $T_2W$  images as those in the DIR sequence, while keeping sufficient flow suppression effects in carotid artery imaging. In addition, the acquisition time for iMSDE-A was a half of that for the DIR. All of the above results indicated that the optimized sequence may be appropriate and practical for multiple contrast 3D vessel wall screening.

## **Chapter 6: Volume Isotropic Simultaneous Interleaved Black- and**

## **Bright-Blood Imaging: A Novel Sequence for Contrast-Enhanced Screening of Brain Metastasis**

Contrast-enhancement (CE) MRI is a reliable modality for screening brain metastasis. The new sequence design with the iMSDE-A technique for fast and interleaved bright- and black-blood acquisitions was presented for brain metastasis screening. Blood suppression effectiveness, lesion contrast and acquisition speed in the new design was compared with the previously proposed bright- and black-blood approach in an earlier report. The results proved the following: MSDE can suppress the blood signal even after contrast media is injected; the new technique can acquire both black- and bright-blood images simultaneously within a practical acquisition time; and the potential exists to improve diagnostic performance in metastasis screening.

## **Chapter 7: Conclusion and Future Work**

Based on the above developments and findings, the present work contributed to the progress of MR imaging techniques and hence, clinical diagnostic medicine through the improvements in image quality and widening of clinical usefulness.

The persistent challenge in MSDE technical development is maximizing the  $m_1$  value while minimizing the signal loss. Several new preparation designs based on adiabatic pulses have been reported recently. Indeed, the adiabatic pulse is known to be less sensitive to  $B_0$  and  $B_1$  inhomogeneity effects, and may be a candidate of future MSDE pulse design. However, other factors of signal loss in the preparation, such as the effects of eddy currents and relaxation, have not been sufficiently assessed to date and further optimization is necessary.

The motion effect is one of the other considerations required in MSDE sequence development. For instance, when MSDE is applied to the heart or other upper abdominal organ, motion effects have to be compensated, while maintaining sufficient signal suppression in the targeted flow. When MSDE is applied to arterial signal suppression but not to the vein, an optimized motion-sensitized gradient design is required. The first order

motion compensation design, called acceleration dependent preparation, has possibilities as initial results have been reported. Adopting a motion control design to the latest optimized MSDE design will be the next step in development.

To make the MSDE design sensitive to diffusion is another, but challenging, topic. Theoretically, MSDE becomes more sensitive to diffusion than to fluid flow when used with a stronger MSG. In this case, however, further compensation for the effects of  $B_0$  and  $B_1$  inhomogeneity, eddy currents and relaxation is required, as stronger gradients and longer preparation time are used.