Improvement of the Image Quality of Black-blood Magnetic Resonance Imaging with the Subtraction Double Inversion Recovery Technique

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ABSTRACT

Black-blood images acquired with the double inversion recovery (IR) sequence in cardiovascular magnetic resonance imaging are commonly applied to distinguish the vessel wall from the lumen to evaluate vascular pathology. However, inadequate suppression of blood signals may introduce artifacts and cause mistakes. The objective of the current study was to determine whether subtraction double IR black-blood imaging improved the image quality.

11 scans from four rabbits were scanned using the conventional and subtraction T1 weighted double IR imaging. The subtraction method involved two scans with a third IR sequence with a series of inversion time (TI) settings in one of them. Each black-blood image was qualitatively evaluated based on contrast-to-noise ratio (CNR), signal-to-noise ratio (SNR), and noises.

Using the best TI setting (575 ms), subtraction black-blood imaging yielded significantly better black-blood effects with a 48.6% increase in mean CNR between the area of the left carotid artery and adjacent paravertebral muscles (PM) and a 30.7% increase in mean CNR between the area of the left jugular vein and adjacent PM compared with the conventional method (5.65 vs. 3.81 and 6.8 vs. 5.21, both p values < 0.05). The subtraction black-blood imaging did not significantly deteriorate image quality regarding noises and mean SNRs in the area of PM.

Subtraction double IR black-blood imaging is better than the conventional method in black-blood effects of blood signals.

Cardiovascular magnetic resonance (MR) imaging without the need of contrast media is common in current clinical practice. Black-blood MR images are acquired with sequences designed to null the signal of flowing blood [1]. These images are essential for anatomic assessment of the heart and vascular structures to diagnose cardiovascular disease, such as myocardial disease, intramural hematoma, intraluminal dissection or vascular plaque [2, 3]. Several techniques have been used to null the bright-blood signal in cardiovascular MR imaging applications, such as double inversion recovery (IR) magnetization preparation [1, 3].

Conventionally, double IR sequences are designed specifically to null the signal from flowing blood. The pre-pulse portion is made of two 180° radiofrequency pulses: a nonselective 180° pulse, which inverts all of the protons in the field, immediately followed by a slice-selective 180° pulse, which reverts the protons in the imaging slice back to their original alignment, leaving all protons outside of the imaging slice inverted. Double IR sequences begin imaging when the magnetization vectors of the flowing blood crosses...
the null point — the inversion time [2, 4]. However, an inadequate nulling of blood signals may introduce artifacts and cause mistakes.

In this study, we established an animal model to evaluate a modified protocol of conventional single-shot double IR turbo fast low angle shot gradient echo (turboFLASH) T1 weighted imaging using a subtraction method. It involved two scans with a third IR sequence with a series of inversion time settings in one of them.

MATERIALS AND METHODS

The animal model

Four adult male New Zealand White rabbits, ranging in weight from 3.1 to 4.4 kg, were used in this study. The animal use protocol was reviewed and approved by the Institutional Animal Care and Use Committee (IACUC). Animals were housed in the laboratory animal resource center under standard conditions during the entire study period. Anesthesia was induced and maintained with 5% and 3% isoflurane (Halocarbon Laboratories, River Edge, NJ) gas anesthesia, respectively. MR scans were repeatedly performed on day 0, 7 and 14.

The MR scan protocol

All MR imaging examinations were performed with a 1.5-Tesla scanner (Magnetom Sonata, Siemens Medical Solutions, Erlangen, Germany) equipped with high-performance 3-axis gradient systems. Animals were placed in the prone position inside the magnet bore at the isocenter and a standard transmit/receive bird-cage human head coil was used. In addition to the triplane gradient echo localizer pulse sequence, the two-dimensional (2D) single-shot double IR turboFLASH T1 weighted imaging scan protocol included: (1) the conventional black-blood imaging with four excitations (NEX = 4), (2) the conventional black-blood imaging with two excitations (NEX = 2), and (3) 15 sets of two-excited bright-blood imaging owing to an additional non-slice-selective IR with a sequence of TI settings (225 ms, 250 ms, 275 ms,… 575 ms). Except for the third IR pulses and number of excitations, all T1 weighted images covered same scan areas in entire animal necks from medullo-cervical junction to aortic arch with identical parameter settings as follows: TR / TE of 800 / 1.51 ms, flip angle of 8°, receiver bandwidth of 470 Hz / Px, slice thickness of 4.0 mm, number of slices = 20, matrix size = 120 x 192, and field of view = 166 x 167 mm. Spectral fat saturation was provided by the MR manufacturer to produce the one-step post-processing bright-blood images. These images were subsequently subtracted from the two-excited conventional black-blood images to obtain the two-step post-processing black-blood images, the so-called two-excited subtraction black-blood images as shown in Fig. 1. These operations generated 15 sets of subtraction images with a different TI value. On the other hand, the scan time was identical between the four-excited conventional black-blood images and the two-excited subtraction black-blood images.

The objective evaluation of the MR images was based on the signal intensity (SI) within manually drawn regions of interest (ROIs), which were placed by the radiologist (S.M.H.) who had 3 years of experience in cardiovascular imaging. The images were evaluated in a single section at the level of neck proximal to the bifurcation of left jugular vein. The inspected ROIs included the areas of the left carotid artery (LCA), left jugular vein (LJV), and the paravertebral muscles (PM) of each animal. The air outside the object was also taken. An effort was made to avoid circling the vascular wall when drawing ROIs.

As the geometric patterns between the conventional black-blood images and 15 sets of subtraction black-blood images were exactly identical, the ROIs from the image with best anatomical information compared to others in the same scan time could be copied and applied to others.

Noise was defined as the standard deviation of the SI within air. Signal-to-noise ratios (SNR) and contrast-to-noise ratios (CNR) values were calculated with the following equations: SNR = SI_{PM}/N, CNR_{LCA} = | (SI_{LCA} - SI_{PM}) | /N and CNR_{LJV} = | (SI_{LJV} - SI_{PM}) | /N, where SI_{PM} was the SI in the PM of the animal, SI_{LCA} was the SI in the area of the LCA, SI_{LJV} was the SI in the area of the LJV, and N was the noise.

Statistical analysis

In the objective evaluation of the two types of black-blood images, data were expressed as mean ± standard deviation. Further analysis was performed with the mean. A paired t test was used to analyze observed differences of noises, SNRs, and CNRs between the four-excited conventional black-blood images and the two-excited subtraction black-blood images. A p value less than 0.05 was considered statistically significant. Data documentation and statistical analyses were performed using Excel (version 2010, Microsoft).

RESULTS

Twelve MR scans were performed on schedule. One scan showed motion artifacts owing to the inadequate anesthesia and resulted in 11 data subjected to statistical analysis.
The images had better quality with higher CNR_{LCA} and CNR_{LJV} as the third TI increased. Among 15 sets of subtraction black-blood imaging, 575 ms of TI had the best CNR_{LCA} (5.65 ± 2.36) and CNR_{LJV} (6.8 ± 2.22) (Fig. 2). As 575 ms was the upper limit of the pulse sequence of the machine, the image characteristics between the conventional black-blood images and subtraction black-blood images with a 575 ms of the third TI were compared (Fig. 3).

**Image characteristics between two types of black-blood images**

Using the optimal TI setting (575 ms), two-excited subtraction black-blood images yielded significantly better black-blood effects of blood signals with a 48.6% increase in mean CNR_{LCA} and a 30.7% increase in mean CNR_{LJV} compared with the four-excited conventional black-blood images (5.65 ± 2.36 vs. 3.81 ± 0.8, 6.8 ± 2.22 vs. 5.21 ± 1.33, respectively, both with p < 0.05) (Table 1). The subtraction black-blood imaging did not significantly deteriorate image quality.
Figure 2. CNRs of subtraction images increased as the third TI increasing. **a.** CNR of left carotid artery, **b.** CNR of left jugular vein.

CNR = contrast-to-noise ratio

Figure 3. Comparison of the conventional black-blood images and subtraction black-blood images. **a.** Four-excited conventional black-blood image, **b.** Two-excited conventional black-blood image, **c.** Two-excited bright-blood image with a third TI setting (TI = 575 ms), **d.** Two-excited subtraction black-blood image. The CNRs of left carotid artery and left internal jugular vein were higher than that on the four-excited conventional image objectively.
Qualitative Improvement of Black-blood MRI

The MR scan time and the post-processing time

The MR scan time of the four-excited conventional black-blood imaging and the two-excited subtraction black-blood imaging was identical (80 seconds). The post-processing time was about 1 minute per case in average.

DISCUSSION

Black-blood imaging may be achieved using spatial saturation. However, it is susceptible to artifacts from slow flowing spins [5, 6]. Thus, a double IR pulse sequence was developed for blood signal suppression since more than 20 years ago [7]. It is available on most current commercial MR machines and can be combined with almost any scanning methods, such as fast spin echo (FSE), steady-state free precession (SSFP) and turboFLASH sequences [4, 7, 8]. Although black-blood imaging with the FSE sequence using a multislice acquisition method is feasible [4, 6], relatively long scan time and higher motion sensitivity are the disadvantages [1, 9].

To minimize motion related artifacts due to long scan time, fast breath-hold black-blood imaging with the SSFP or turboFLASH sequence using a single-shot technique was introduced [7, 9]. According to Lin et al, 2D double IR SSFP imaging has better image quality compared with the 2D double IR FSE sequence under fast heart rate conditions [9]. Bornstedt et al showed that three-dimensional (3D) stacks with the proposed motion sensitized segmented steady-state black-blood gradient echo technique (MSDS) enabled time-efficient coverage of large areas of the vessels without compromising wall-lumen CNR compared to conventional double IR turbo spin and gradient echo images [3]. The major disadvantage of SSFP is very sensitive to B0 inhomogeneities and small frequency shifts leading to substantial reduction in the transverse steady-state magnetization and, thus, to band-shaped signal losses [10].

In our study, black-blood imaging was achieved with a 2D single-shot double IR turboFLASH sequence, which has shorter acquisition time compared to the FSE and requires less of the hardware to maintain B0 homogeneities compared to the SSFP theoretically. Although double scans (two excitations in each) and post-processing are required for the subtraction black-blood method, the MR acquisition time itself was identical to the conventional black-blood method with four excitations, the default setting for the clinical practice at our institute. The repeated excitations are designed to compensate the poor SNR nature of turboFLASH sequences.

Conventionally, triple IR pulse sequence means a pair of slice-selective and nonselective 180° inversion pulses to null the blood flow signal followed by a third inversion pulse to null the fat signal [11]. The inversion time of the third IR is around 120 to 180 ms at 1.5-Telsa field strength [12, 13]. In our study, the third IR was to invert the blood signal for acquiring later subtraction images, instead of suppression of signals from fat. After adding the third IR, the flowing blood revealed the high SI and the stationary tissue exhibited the low SI (Fig. 1a), although there was a slightly increased SI of the stationary tissue as the third TI increasing.

The time delay between two scans in the subtraction method may increase the risk of motion-related misregistration artifacts as shown at one of our data. This may be the major disadvantage of our subtraction double IR black-blood imaging. To circumvent this, rearrangement of the two scans into one condensed sequence is planned for future studies.

This study has limitations that should be addressed. Firstly, the subtraction double IR black-blood imaging was only compared with conventional one using turboFLASH sequences. The FSE and SSFP-based sequences were not addressed. Secondly, only 2D sequences were tested in this study. The efficiency of the subtraction method in 3D black-blood imaging is not yet clear. Thirdly, only objective evaluations based on SI measurements were performed. The subjective impacts of the imaging technique on the readers are not clear. Finally, the protocol was only tested on a limited number of animals.

In conclusion, the subtraction turboFLASH sequence

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<tr>
<th>MR pulse sequences</th>
<th>Conventional black-blood images</th>
<th>Subtraction black-blood images</th>
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<tbody>
<tr>
<td>CNR&lt;sub&gt;LCA&lt;/sub&gt;</td>
<td>3.81 ± 0.8</td>
<td>5.65 ± 2.36</td>
</tr>
<tr>
<td>CNR&lt;sub&gt;LJV&lt;/sub&gt;</td>
<td>5.21 ± 1.33</td>
<td>6.8 ± 2.22</td>
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<tr>
<td>Noise</td>
<td>11.51 ± 1.74</td>
<td>13.58 ± 3.81</td>
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<tr>
<td>SNR</td>
<td>7.65 ± 1.12</td>
<td>6.91 ± 2.21</td>
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Note: Statistical significances were calculated using the paired student t test.
is an alternative 2D double IR black-blood imaging. Compared to the conventional method, the new protocol showed better blood signal black-blood effects and CNR without compromising image quality in terms of noises and SNR under the same image acquisition time. Such improvements in imaging quality may promote the diagnostic capacity of cardiovascular magnetic resonance imaging.

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REFERENCE