Introduction

Black-blood Dynamic Contrast-Enhanced (DCE) MRI of vessel wall has been used to detect early atherosclerosis\(^1\) and monitor plaque progression\(^2\). Unlike traditional bright-blood techniques, thin vessel walls with early lesions can be clearly delineated without interference from luminal signal in black-blood DCE MRI. However, most existing black-blood DCE-MRI techniques for early diseased vessel walls use a simplified area under the curve (AUC) analysis\(^3\), as the difficulty to extract arterial input function (AIF) from the black-blood DCE MRI precludes the kinetic analysis. To accurately estimate kinetic parameters for early atherosclerotic lesions, a sequence of interleaved black-blood and bright-blood acquisition with high spatial and temporal resolution is needed. Recently, several sequences have been proposed, including IBBI\(^4\), BB-SHILO\(^5\), and SRDIR\(^6\). However, the signals from black-blood and bright-blood images are not comparable and require complex conversion for kinetic analysis in IBBI and BB-SHILO. In SRDIR, the blood suppression is not ideal for DCE acquisition and its temporal resolution is low. In this study, we propose a conversion-free interleaved black-blood and bright-blood sequence (cIBBI), with excellent blood suppression and high spatial resolution in black blood images as well as high temporal resolution in bright blood images for AIF.

Methods

Black Blood Imaging: To create a T1-weighted black blood image, we used a TFE based sequence with a pre-pulse combining a non-selective Saturation-Recovery (SR) and Quadruple Inversion-Recovery\(^7\) (QIR), as shown in the left figure of Fig. 1a. The SR pulse can generate T1 weighting and avoid interference from black-blood and bright-blood segments. The QIR pre-pulse is used to suppress the blood in a wide range of T1. Blood flow into the imaging field will experience two IR pulses, while the tissue in the imaging plane will experience one SR pulse and four IR pulses. As a result, by optimizing the parameters of TS/TI1/TI2 (Fig. 1) according to:\[^{1}\hspace{1mm}TS,\hspace{1mm}T1,\hspace{1mm}T2\hspace{1mm}][\hspace{1mm}arg\hspace{1mm}=\hspace{1mm}min\hspace{1mm}\int_{T1_{\max}}^{T1_{\min}}M_{\text{longitudinal}}\hspace{1mm}(T1\hspace{1mm})\hspace{1mm}(\hspace{1mm}M_{\text{longitudinal}}\hspace{1mm}is\hspace{1mm}the\hspace{1mm}longitudinal\hspace{1mm}magnetization\hspace{1mm}of\hspace{1mm}blood,\hspace{1mm}and\hspace{1mm}T1_{\max}\hspace{1mm}and\hspace{1mm}T1_{\min}\hspace{1mm}are\hspace{1mm}the\hspace{1mm}maximand\hspace{1mm}and\hspace{1mm}min\hspace{1mm}T1\hspace{1mm}of\hspace{1mm}blood\hspace{1mm}during\hspace{1mm}dynamic\hspace{1mm}imaging,\hspace{1mm}T1_{\max}\hspace{1mm}=\hspace{1mm}200\hspace{1mm}msec,\hspace{1mm}T1_{\min}\hspace{1mm}=\hspace{1mm}1500\hspace{1mm}msec,\hspace{1mm}respectively,\hspace{1mm}the\hspace{1mm}signal\hspace{1mm}of\hspace{1mm}blood\hspace{1mm}can\hspace{1mm}be\hspace{1mm}suppressed\hspace{1mm}in\hspace{1mm}a\hspace{1mm}wide\hspace{1mm}range\hspace{1mm}of\hspace{1mm}T1,\hspace{1mm}with\hspace{1mm}tissue\hspace{1mm}recovery\hspace{1mm}according\hspace{1mm}to\hspace{1mm}the\hspace{1mm}T1\hspace{1mm}value.\hspace{1mm}]

Bright Blood Imaging: To obtain comparable bright blood images, the bright blood sequence, especially its timing, is designed identically to the black blood acquisition, except that we replace the slice-selective pulses of QIR with non-selective pulses to generate T1-weighted black blood signal (right figure of Fig. 1a).

Interleaved Timing Diagram: To obtain black-blood and bright-blood images simultaneously, segmented acquisition (black-blood segment and bright-blood segment were interleaved) was used (Fig.3). To achieve high spatial and temporal resolution for kinetic analysis, we used different resolutions in black-blood and bright-blood acquisitions. Because vessel walls with early lesions are very thin and their signal changes slowly, they should be imaged with high spatial resolution. On the other hand, the luminal signal (AIF) changes rapidly, demanding higher temporal resolution. Hence, spatial resolution for black-blood acquisition was designed 4 times higher than bright blood images, and the temporal resolution for bright blood imaging was 4 times higher than black blood imaging.

MR Imaging: After institutional review board approval, a healthy New Zealand rabbit (3kg) was scanned on a 3.0T MR system (Achieva, TX, Philips) using a 8-channel knee coil. 0.1 mmol/kg of contrast (Gd-DTPA) was injected coincident with the third acquisition (black-blood dynamic) at a rate of 2ml/s following with 15ml saline solution. The scan parameters: TR/TE 7.5/3.7ms, flip angle 30°, TFE factor 20, TS/T1/T2= 110/170/60ms, FOV 80×80mm, slice thickness 6mm, 1 slice. Black blood images have a spatial resolution of 0.5x0.5mm, 15 dynamic scans, and temporal resolution 7.87s; while bright blood images have a spatial resolution of 0.25x0.25mm, 60 dynamic scans, and temporal resolution 1.97s. Image analysis: Images were analyzed using a custom program written in Matlab (Mathworks Inc.). First, contours were manually drawn on each frame of the black-blood dynamic acquisition to segment the vessel wall. Then, by assuming a linear relationship between the MRI signal intensity and the contrast concentration, the normalized average intensity curve (SI(t)−SI(0))/SI(0), where SI(t) is the intensity at time t of the vessel wall in black-blood images (Ct) was extracted as the contrast concentration curve for kinetic analysis. As black blood and bright blood images are acquired at different resolutions, zero-padding is used to expand the black-blood matrix size to 160x160 before Fourier transform, so signals from black blood and bright blood images are comparable. Similarly to Ct, the AIF (Cp) was calculated from the luminal in black-blood images. The Patlak model\(^8\) was then used to calculate transfer constant (Ktrans) and partial plasma volume (vP) of the artery. The intensity of a muscle region is also reported to test the signal consistency between black-blood and bright-blood acquisition.

Results

Fig.4 shows example images. Blood suppression is excellent after contrast arrival, and the vessel wall can be clearly seen in the black-blood images with high spatial resolution. At the same time, the bright-blood image is distinct, with a high temporal resolution of 1.97s. The Ct and AIF curves of the rabbit aorta are shown in Fig.5. Calculated Ktrans and vP are 0.074 min\(^{-1}\) and 0.165, respectively, reasonable in a normal artery by compared to values reported in previous study\(^9\). Also, average muscle signals in the black blood and the bright blood images are nearly the same, as shown in Fig.6.

Conclusion

In this study, a conversion-free Interleaved Black Blood and Bright Blood DCE-MR Imaging (cIBBI) technique was developed to evaluate vessel wall perfusion of early lesion with excellent blood suppression. It offers simultaneous high spatial-resolution black blood acquisition to better image thin vessel walls and high temporal-resolution black-blood and bright-blood acquisition to catch the rapidly changing signals of AIF for kinetic analysis. Moreover, the intensities obtained from the black-blood and bright-blood images are comparable and can be directly used in kinetic analysis without conversion.