Averaging Keyhole Pulse Sequence with Presaturation Pulses and EXORCYCLE Phase Cycling for Dynamic Contrast-Enhanced (DCE) MRI

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INTRODUCTION

Dynamic contrast-enhanced (DCE) MRI is a powerful tool to evaluate tissue perfusion. Concentration of contrast agent can be quantitatively measured with spoiled gradient echo (SPGR) sequence with short TR. However *in vivo* SPGR perfusion measurement can be compromised because of potential inflowing of non-saturated blood within the slice of interest (time-of-flight (TOF) effect). For acquiring DCE-MRI with the SPGR sequence, presaturation is generally used for removing TOF effect. However if the saturation is not complete, residual transverse magnetization generates ghosting artifacts and compromises quantitative analysis.

EXORCYCLE, a phase cycling method for removing ghost caused by incomplete pulse flip angle, has been applied to multi-dimension liquid NMR [1]. The authors introduced the EXORCYCLE phase cycling into a modified keyhole pulse sequence in order to remove ghosting artifacts while maintaining a very high temporal resolution.

METHODS

The EXORCYCLE phase cycling for SPGR with a presaturation pulse is shown in Fig. 1 (Left). Each phase encoding step is repeated twice with the phase of both the excitation pulse and receiver changed from 0° to 180°. Odd- and even-echoes are averaged, which removes both ghosting artifacts due to imperfect saturation and DC offsets, and improves signal-to-noise ratio.

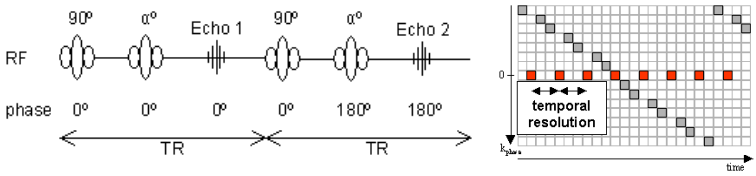

Fig 1. Left: EXORCYCLE phase cycling for averaging keyhole pulse sequence with presaturation. **Right:** Phase encoding data acquisition scheme for high temporal resolution keyhole sequence.

The phase cycling was incorporated into a keyhole sequence for high temporal resolution DCE-MRI with following characteristics,

- Peripheral lines of k-space were renewed every 7 acquisitions of central lines of k-space (Fig. 1, Right). A similar acquisition protocol has been previously applied in fMRI [2] and 3D angiography [3]. This approach differs from conventional keyhole where only the center of k-space is generally acquired during a dynamic scan. This current technique has the advantage of limiting the k-space discontinuity, which is particularly acute during contrast agent injection.
- Both gradient- and RF-spoiling were performed. RF spoiling was applied by the frequency jump and reset after the gradient spoiling pulses and before the next TR [4], which could be combined with the EXORCYCLE phase cycling.

We applied the current approach to the measurement of an arterial input function (AIF) in the rat abdominal aorta. The DCE-MRI experiment was performed on a 4.7 T horizontal MRI system (UNITYINOVA, Varian, Palo Alto, CA) with a 6-cm inner diameter quadrature birdcage coil (Varian). Parameters for the designed keyhole sequence were: TR/TE = 13.9/2.3 ms, flip angle (α) = 15°, FOV = 6 x 6 cm^2, slice thickness = 5 mm, matrix = 128 x 96, zero-filled to 128 x 128 for data construction. Number of updated central phase-encoding steps was 5. Temporal resolution was 0.5 s (= TR x 18 phase encode steps x 2 averaging). Slice plane was axial and through a kidney. In order to suppress TOF, a saturation band was applied perpendicular to the slice plane covering the entire abdominal aorta. Delay for saturation recovery was 10 ms. 0.8 mmol/kg body weight Gd-DTPA (Schering AG, Berlin) was injected from a tail vein (injection speed 0.5 mL/s) during DCE-MRI acquisition. Averaging and Fourier transform were carried out using software developed in-house on IDL (Research System, CO).

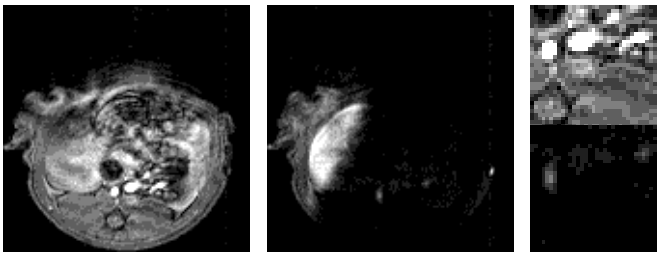

Fig 2. DCE-MRIs obtained by the keyhole sequence shown in Fig. 1. **Left**: without saturation band pre-contrast. **Middle**: right after contrast agent injection. **Right**: Expanded images (1.5 cm x 1.5 cm) around the regions including abdominal aorta, vein, spine, and surrounding tissues. Phase encoding axis is vertical.

RESULTS and DISCUSSION

MR images obtained by the modified keyhole sequence are shown in Fig. 2. No ghosting artifacts were observed in both the saturated (arteries, veins, a spine, back muscles) and unsaturated regions (a kidney, subcutaneous fat). The shape of aorta lumen obtained around injection period was slightly blurred along phase encoding axis (Fig. 2, right-bottom). The AIF obtained successfully with 0.5-s temporal resolution is shown in Fig. 3. However, the AIF curve had discontinuity around injection time and the number of isolated high-intensity data points was seven (Fig. 3, inset), which was equivalent to the number of central lines acquisitions per entire k-space (Fig. 1, Right). This discontinuity of the AIF curve may be caused by the mismatch of the acquisition timing between the central and the peripheral lines of k-space. This might be eliminated by interpolating the outer region of k-space as described in [3]

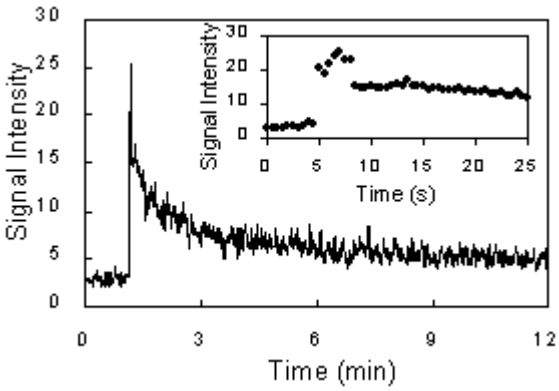

Fig 3. AIF from abdominal aorta lumen with 0.5-s temporal resolution. **Inset**: around injection time (25-s).

In this study we have modified the conventional keyhole to achieve high temporal resolution DCE-MRI without suffering from TOF or ghosting artifacts. This was done by inserting 1) a presaturation pulse 2) EXORCYCLE phase cycling, and, 3) by sampling the outer region of k-space more frequently. We anticipate that this technique would lead to better quantification of tissue perfusion.

REFERENCES

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