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Fat suppression with short inversion time inversion-recovery and chemical-shift selective saturation: a dual STIR-CHESS combination prepulse for Turbo Spin Echo pulse sequences

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Running title: Hybrid fat suppression in TSE-MRI

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Abstract

Purpose

To test a newly developed fat suppression magnetic resonance imaging (MRI) prepulse that synergistically uses the principles of fat suppression *via* inversion recovery (STIR) and spectral fat saturation (CHESS), relative to pure CHESS and STIR. This new technique is termed dual fat suppression (Dual-FS).

Materials and methods

To determine if Dual-FS could be chemically specific for fat, the phantom consisted of the fat-mimicking NiCl_2 aqueous solution, porcine fat, porcine muscle, and water was imaged with the three fat-suppression techniques. For Dual-FS and STIR, several inversion times were used. Signal intensities of each image obtained with each technique were compared. To determine if Dual-FS could be robust to magnetic field inhomogeneities, the phantom consisting of different NiCl_2 aqueous solutions, porcine fat, porcine muscle, and water was imaged with Dual-FS and CHESS at the several off-resonance frequencies. To compare fat suppression efficiency *in vivo*, ten volunteer subjects were also imaged with the three fat-suppression techniques.

Results

Dual-FS could suppress fat sufficiently within the inversion time of 110-140 ms, thus enabling differentiation between fat and fat-mimicking aqueous structures.

Dual-FS was as robust to magnetic field inhomogeneities as STIR and less vulnerable than CHESS. The same results for fat suppression were obtained in volunteers.

Conclusion

The Dual-FS-STIR-CHESS is an alternative and promising fat suppression technique for turbo spin echo MRI.

Keywords: magnetic resonance imaging (MRI); chemical-shift selective (CHESS); short TI inversion recovery (STIR), fat suppression

Introduction

Turbo spin echo (TSE) or fast spin echo (FSE) pulse sequences for magnetic resonance imaging (MRI) have been widely used as faster alternatives to conventional spin-echo (SE) providing similar contrast properties (1). The most significant contrast difference between similarly weighted TSE and SE images relates to the much increased signal intensity of fat in TSE images compared to that with SE images. The bright fat phenomenon arises mainly from the lack of J-coupling-dependent dephasing of coupled lipid protons (2,3). Increased signals from fat on T2-weighted images can obscure pathologies with elongated T2 in or adjacent to the fatty tissue. In order to address this problem, two types of prepulse fat-suppression techniques have been widely used: spectral saturation, represented by chemical-shift selective sequence (CHESS), and short inversion time inversion recovery (STIR) sequence. Both of these fat suppression techniques have advantages and limitations, as explained below.

The CHESS technique is based on the fact that the resonance frequencies of water and fat differ by ≈ 3.5 ppm. Specifically, the CHESS pre-pulse module consists of a narrow bandwidth radiofrequency (RF) 90° excitation pulse used to selectively saturate fat (4) and gradient pulses to

dephase fat signal. In this way, an image depicting only aqueous tissues can be generated. The resonance frequency of fat, however, is magnetic field-dependent and, therefore, fat suppression homogeneity with CHESS can be degraded due to magnetic field inhomogeneities. Because magnetic field inhomogeneities are mainly caused by the patient, fat suppression quality with CHESS is patient dependent and therefore its consistency in the clinical setting is less than ideal (5).

On the other hand, STIR pulse sequences are based on the principle of inversion recovery with a short inversion time (TI), so to null tissue signals with the T1 of fat, which is the shortest T1 in the human body (6). The RF excitation pulse of the pulse sequence is applied at the null time-point of fat's longitudinal magnetization recovery. This null time point is calculated by multiplying 0.693 by T1, which gives $\approx 173\text{ms}$ at 1.5T. STIR techniques are much less vulnerable than CHESS techniques to the presence of magnetic field inhomogeneities and therefore produce more consistent fat suppression quality in the clinical setting. The main disadvantage of STIR techniques relates to the fact that it is not chemically specific: any aqueous tissue with a T1 value similar to fat, eg, mucous, hemorrhage, proteinaceous fluid, gadolinium, and melanin will also

appear devoid of signal in STIR images (7,8).

A more practical fat suppression technique should have both the high chemical specificity of CHESS and the low vulnerability to magnetic field inhomogeneities of STIR. A one-RF prepulse Dual-FS technique that uses a chemically selective 180° prepulse to invert only protons of fat, and the imaging pulse sequence is applied at the null point of fat, has been described in the literature (9). In this work, a different Dual-FS fat suppression technique --termed hereafter Dual-FS because it uses dually the two main principles of fat suppression -- is described and studied quantitatively with phantoms and human subjects in the head.

Materials and methods

All MR imaging was performed using a 1.5 T whole-body MR unit (MAGNETOM Symphony Maestro Class, Siemens AG, Erlangen, Germany) using a head coil and a neck coil combination.

Pulse sequences

Three sequences were tested, specifically: STIR-TSE, CHESS-TSE, and the Dual-FS-TSE. Common sequence parameters were as follows: repetition time (TR), 3500ms; echo time (TE), 95ms; echo-train-length (ETL) 17; slice thickness, 5 mm; number of signals averaged (NSA), 1; field of view (FOV), 230 mm; image matrix, 256x256; bandwidth, 100Hz.

The timing diagram of the Dual-FS prepulse is shown in Fig. 1. It consists of a non-selective 180° inversion pulse followed immediately by a chemically selective excitation pulse tuned the resonance frequency of fat and dephasing gradient pulses along the three orthogonal directions. The TSE imaging pulse sequence is applied at a time TI from the inversion pulse.

Phantom experimentation

Phantom experiments were conducted for the specific purposes of: 1) To calibrate the Dual-FS prepulse and determine the concentration of Nickel chloride (NiCl_2) that in aqueous solution produces the closest T1 to that of fat. 2) Conduct experiments to determine the conditions for which fat-mimicking aqueous samples could be distinguished from fat using Dual-FS-TSE. 3) To study comparatively the vulnerability to magnetic field inhomogeneities of CHESS-TSE vs. Dual-FS-TSE.

Four cylindrical vials containing different aqueous solutions of NiCl_2 (concentrations: 5, 6, 7, and 8mM) and one cylinder with porcine fat were prepared and imaged with IR-TSE pulse sequence using several inversion times, specifically: 50, 80, 110, 140, 170, 200, or 230ms. The signal intensity of each sample was measured with a circular region-of-interest (ROI) with an area of 0.8 cm^2 using SyngoTM, which is software provided by the manufacturer of the MR unit used. As shown in the results section, the 6mM NiCl_2 solution had the closest T1 relative to porcine fat and therefore was used for subsequent experiments.

A second phantom was used to determine if fat-mimicking solutions could be distinguished from fat with the Dual-FS-TSE technique. The phantom consisted of four vials: the fat-mimicking NiCl_2 aqueous solution, porcine fat,

porcine muscle, and water. This phantom was imaged with CHESS-TSE, STIR-TSE and the Dual-FS-TSE. For the last two sequences, several inversion times were used, specifically: 50, 80, 110, 140, 170, 200, or 230ms. This full imaging protocol was repeated eight times: mean and standard deviation (SD) of signal intensities were calculated for each sample.

A third phantom was used to study comparatively the vulnerability to magnetic field inhomogeneities of CHESS-TSE vs. Dual-FS-TSE. This phantom consisted of 4 vials: 6 mM NiCl₂ aqueous solution, porcine fat, porcine muscle, and water. The phantom was imaged with CHESS-TSE and Dual-FS-TSE using several inversion times: 50, 80, 110, 140, 170, 200, or 230ms. Experiments were performed at the resonance frequency and several off-resonance frequencies: specifically offsets of 50Hz, 100Hz, 150Hz, and 200Hz. This full imaging protocol was repeated eight times: mean and SD of signal intensities were calculated for each sample.

Volunteer Testing

This study was approved by the institutional Ethical Committee. Written informed consent was obtained from all volunteer subjects prior to the MR

examination. Ten volunteer subjects (two women and eight men) with an age range of 26-49 years (mean age, 34.5 years) were imaged using the same sequence parameters used for the phantom examination. Oblique-coronal images including the globes and mandibular first molars were obtained to compare the signal intensities of tissues similar to samples of phantom examinations. The signal intensities of the globes, buccal fat, lingual muscle, and muscles in submandibular region were measured using a circular ROI. Mean and SD of signal intensities within 10 images were calculated for each structure. ROI signal intensity measurements were compared among CHESSTSE, STIR-TSE and Dual-FS-TSE methods.

Results

Fat mimicking aqueous sample

Figure 2 shows the signal intensities of four NiCl_2 solutions and porcine fat for different TIs using IR-TSE. All signal intensities decreased with increasing in TI up their respective null points and increased after reaching the minimal signal intensity. The approximate null point of the porcine fat sample was approximately TI of 170 msec and it was best approximated by the 6 mM NiCl_2 solution.

Phantom experimentation

Table 1 lists the mean and SD for signal intensity of the 6 mM NiCl_2 solution, porcine fat, water, and porcine muscle with CHESSTSE and shows that the fat suppression level is about 15-to-1 relative to water.

Signal intensity measurements as function of TI with STIR-TSE and Dual-FS-TSE are shown in Fig. 3a,b, respectively. The signal intensity patterns as a function of TI were nearly identical for all aqueous materials, *ie*, 6 mM NiCl_2 solution, porcine muscle, and water. For the porcine fat sample, however, the signal intensity patterns obtained with the two pulse sequences were markedly

different. Specifically, the signal intensity of the porcine fat was approximately independent of TI with Dual-FS-TSE, giving a nearly constant fat attenuation level of ≈ 22 -to-1 relative to water. Furthermore, the signal intensity of the fat-mimicking 6 mM NiCl₂ aqueous solution could be made to be significantly different from zero by using Dual-FS-TSE at TI values other than 170 msec, the fat null point with STIR-TSE.

Signal intensity measurements as a function of resonance frequency shift with CHESS-TSE and Dual-FS-TSE are shown in Fig. 4a-f, respectively. On Dual-FS-TSE, only the results for inversion times of 50-170 msec are shown, considering the clinical utility. With CHESS-TSE, contrast between muscle and fat remained positive up to off-resonance frequencies of 60Hz. The contrast between water and fat remained positive up to 130 Hz. Dual-FS-TSE using TI of 110-140 msec, however, could keep positive contrast between muscle and fat up to 120 Hz. Contrast between water and fat could not be reversed up to 200 Hz.

Human volunteers

Figure 5a-c shows oblique-coronal images of one volunteers. Incomplete fat suppression could be observed with CHESS (Fig. 5a), especially

around the globes (arrow). Fat suppression was also incomplete with STIR (Fig. 5b), except at a TI of 170 msec. The Dual-FS method (Fig. 5c) also produced regions of incomplete fat suppression at a TI of 50 msec (arrow). At TIs of 110 and 170 msec, however, the signal of fat was homogeneously suppressed (arrow).

Table 2 shows the mean and SD for signal intensity in each anatomical structure with TSE and CHESS-TSE. The mean signal intensity of buccal fat was 105.2. Figures 6a,b shows the mean signal intensity of each anatomical structure at different TIs. With STIR-TSE (Fig. 6a), signal intensity of buccal fat was higher than that of muscle at a TI of less than 170 msec. With the Dual-FS-TSE, the signal intensity of fat was lower than that of muscle, and lower than that of fat with CHESS-TSE, regardless of TI. Image contrast between fat and muscle remained high, regardless of TI.

Discussion

A newly developed Dual-FS-STIR-CHESS fat suppression technique has been described and studied quantitatively with phantoms and volunteers by implementing it as a prepulse to a standard TSE pulse sequence.

A previously described hybrid technique (9), which used a chemically selective 180° prepulse to invert only protons of fat with the imaging pulse sequence being applied at the null point of fat, is very practical and simple to implement. Spectral presaturation by inversion recovery (SPIR) and spectral attenuated inversion recovery (SPAIR) fat-suppression techniques, which are used routinely in many facilities, are based on the similar principle to this Dual-FS technique. The fat-suppression efficacy of these techniques, however, is also limited by magnetic field inhomogeneities (10), similarly to CHESS. For this work, therefore, we combined the two main principles for fat suppression in the form of two prepulses for fat suppression: a nonselective 180° inversion pulse and a chemically selective excitation pulse tuned the resonance frequency of fat.

Phantom results show that Dual-FS-STIR-CHESS-TSE can produce strong fat suppression over the 110-140 msec TI range, thus enabling

fat-suppressed imaging at TI values that differ from the null point of fat. In this way, fat-mimicking aqueous tissues with a T1 close to that of fat can be made visible, and therefore distinguishable, by imaging with Dual-FS-STIR-CHESS at an offset TI different from the fat null time-point. Such Dual-FS-STIR-CHESS with a short TI can produce a sufficiently fat-suppressed image with high signal intensity from aqueous tissues. It is probably advisable to choose a TI offset such that TI is shorter than the null point of fat because most aqueous lesions and structures have longer T1s than fat. This would give highest chance of observing all short T1 aqueous lesions. Furthermore, imaging results with a phantom and a volunteer show that the Dual-FS-STIR-CHESS prepulse is as robust to magnetic field inhomogeneities as the standard STIR and less vulnerable than CHESS.

In summary, a fat suppression technique that combines the high chemical specificity of CHESS with the low vulnerability to magnetic field inhomogeneities of STIR has been described and studied quantitatively with phantoms and human volunteers. In conclusion, Dual-FS-STIR-CHESS is an alternative and promising fat suppression technique for TSE-MRI.

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Table 1. Signal intensity of 6mM NiCl solution, fat, muscle, and water with CHESSTSE.

	6mM NiCl	porcine fat	porcine muscle	water
Mean	1474.8	88.5	376.6	1356.3
SD	13.5	21.9	24.1	15.3

Table 2. Signal intensity of anatomical structures with TSE and CHESSTSE.

	TSE (SD)	CHESSTSE (SD)
Buccal fat	1238.4 (329.6)	105.2 (43.8)
Globes	1175.8 (209.9)	871.2 (50.4)
Lingual muscle	305.1 (63.5)	239.3 (36.0)
Muscles in submandibular region	304.9 (61.2)	305.9 (37.0)

Figure Legends

Figure 1. Pulse sequence timing diagram of the Dual-FS-STIR-CHESS-TSE pulse sequence.

Figure 2. Signal intensity of NiCl_2 aqueous solutions and porcine fat with IR-TSE.

Figure 3. Signal intensity of 6mM NiCl_2 aqueous solution, porcine fat, porcine muscle, and water as measured from **(a)** STIR-TSE images and **(b)** Dual-FS-TSE images: acquired at various TI: values.

Figure 4. Signal intensity of NiCl_2 aqueous solutions, porcine fat, porcine muscle, and water acquired at several frequency bands. CHESS-TSE image **(a)** and Dual-FS-TSE images: TI of 50 **(b)**, TI of 80 **(c)**, TI of 110 **(d)**, TI of 140 **(e)**, TI of 170 **(f)**, TI of 200 **(g)**, and TI of 230 **(h)**.

Figure 5. Oblique-coronal images of one volunteer with **(a)** CHESS-TSE, **(b)** STIR-TSE and **(c)** Dual-FS-TSE method.

Figure 6. Signal intensity of several anatomical structures with **(a)** STIR-TSE and **(b)** Dual-FS-TSE method.

Fig.1

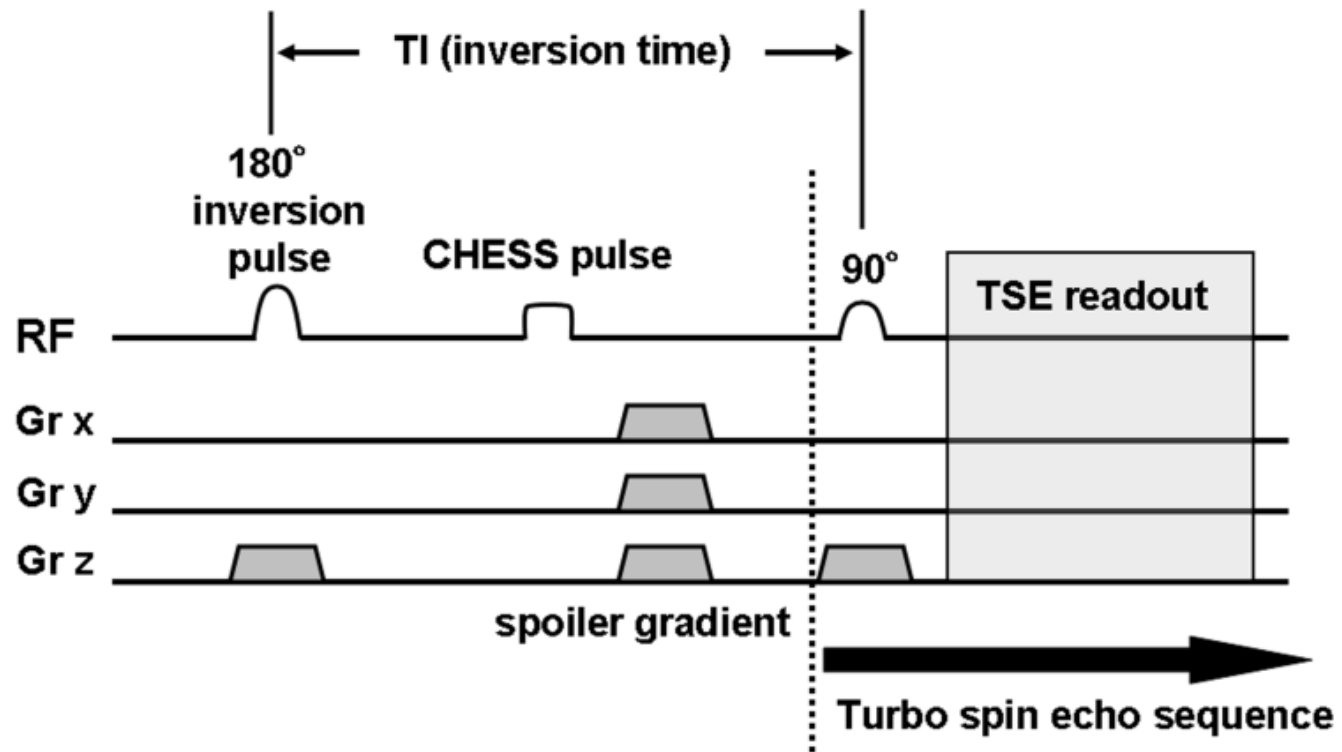


Fig.2

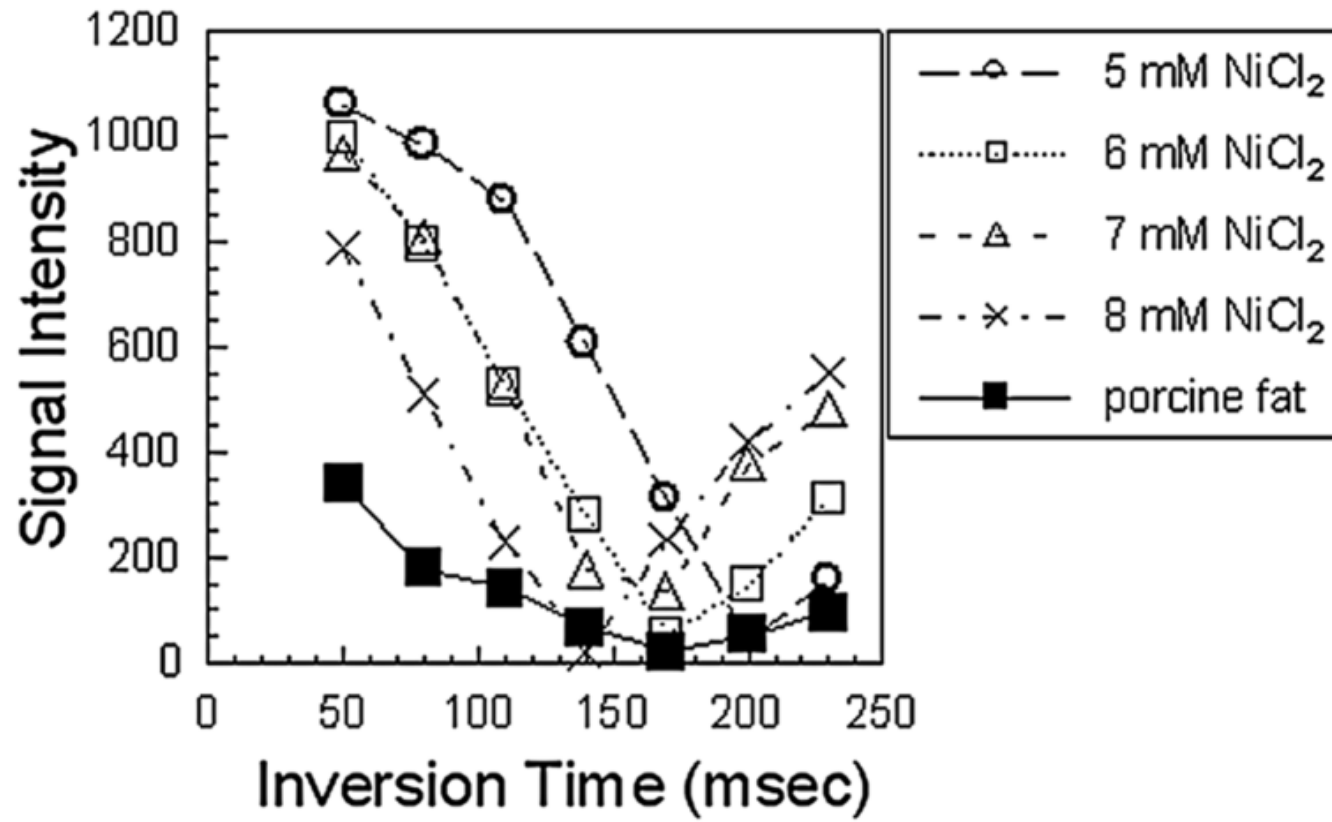


Fig. 2

Fig.3

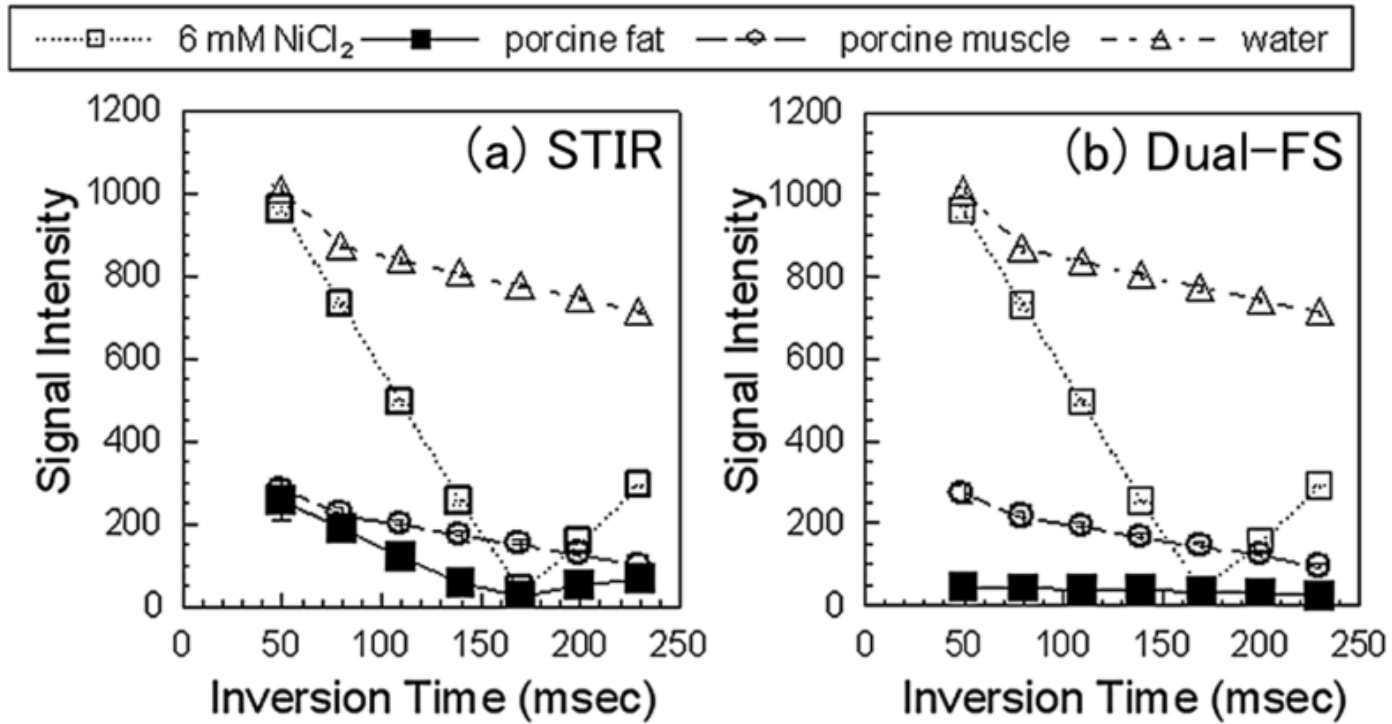


Fig. 3

Fig.4

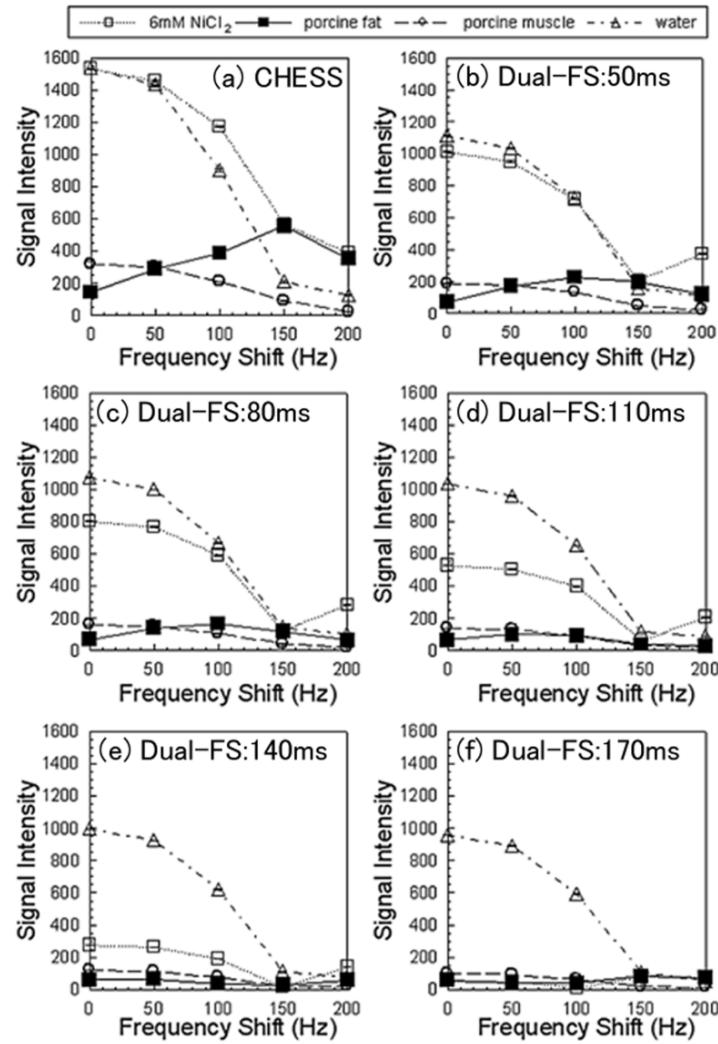


Fig. 4

Fig.5

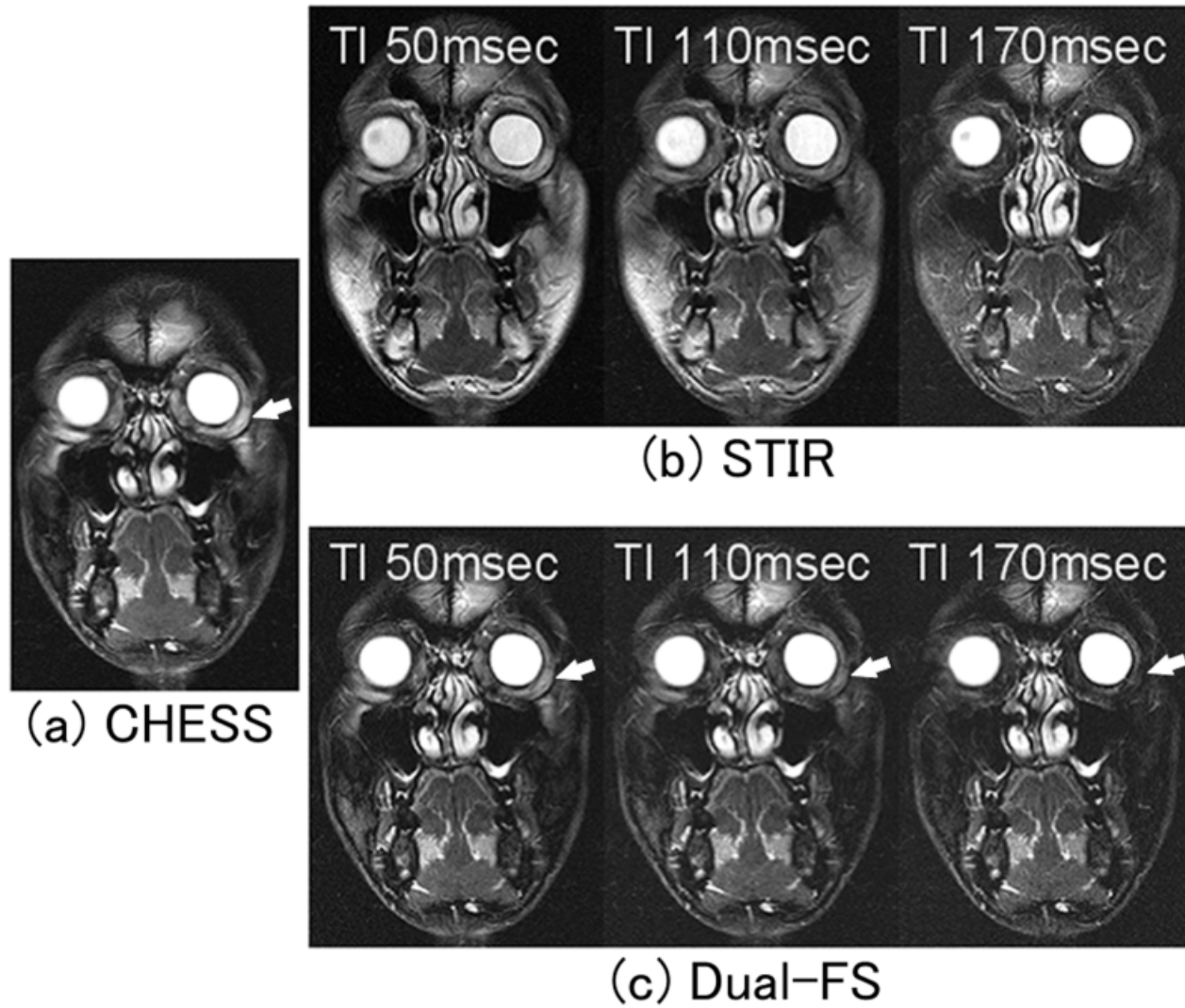


Fig. 5