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The effect of inversion times on the minimum signal intensity of the contrast agent concentration using inversion recovery t1-weighted fast imaging sequence

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Abstract

Background: Inversion recovery (IR) pulse sequences can generate T1-weighted images with a different range of inversion time (TI) to suppress or null the signal intensity (SI) for a specified tissue. In this study, we aimed to investigate the effect of TI values on the concentration of the contrast agent, which leads to a minimum signal intensity, using an inversion recovery T1-weighted 3-dimensional fast-gradient echo imaging sequence.

Methods: A phantom was designed to hold 25 vials which contained different (between 0 and 19.77mmol/L of (Gd-DTPA)) concentrations of the contrast agent. We used the vials of different concentrations to measure SI using IR sequences with different inversion times (TI, 100-3000ms).

Results: The results of this study revealed that the T1 recovery curve did not cross the x- axis for the lower TI. Therefore, a minimum SI can be observed from the concentration of the contrast agent versus SI curves. The findings of this study also revealed that the concentration of the contrast agent, which leads to a minimum SI, is dependent on the TI and the minimum SI will be increased at higher TI concentrations.

Conclusion: In conclusion, when the TI parameter is used to suppress the SI of the specified tissues in clinical studies (e.g., fat suppression or blood suppression in perfusion measurements), it should be chosen with great caution.

Keywords: Inversion Time, T1-Weighted, Signal Intensity, Concentration of Contrast Agent, Null Point.

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Introduction

Many factors such as image parameters (e.g., TR, TE, TI, flip angle), image weighting (e.g., T1, T2, T2*, PD weighted), the magnetic susceptibility of the contrast agent, the magnetic field strength, the pulse sequence parameters, the dose of the contrast agent, the injection rate and bolus volume, the cardiac output and blood volume and the tissue topology may affect the SI (1).

The paramagnetic-metal contrast agents such as Gadolinium-diethylenetriamine-pantaacetic acid (Gd-DTPA) are administered to improve the contrast of the MRI images; while the paramagnetic contrast medium passes through the tissue, it produces a local magnetic field in the homogeneities leading to a reduction in the transverse relaxation time (T2) and longitudinal relaxation time (T1) of the bulk of the tissue. A decrease in T1 typically causes an increase in the signal intensity (SI), whereas a decrease in T2 causes a decrease in the SI (2). The T1-shortening effect is dominant at low concentrations of Gd-DTPA, and the T2-shortening effect is dominant at high concentrations and leads to a decrease in the SI.

The MR signal intensity will depend on the image parameters, the type of imaging sequence used and the magnetic field

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strength (3-5).

Inversion recovery (IR) sequences are commonly used to suppress the SI of a specific tissue such as cerebrospinal fluid (CSF) or fat. IR pulse sequences can generate T1-weighted images with a different range of inversion times (TIs of 85–1238 ms) to suppress or null the SI for a specified tissue (6-8).

Previous studies have shown that the inversion time (TI), repetition time (TR), echo time (TE), different sequences (e.g., inversion recovery and saturation recovery), inflow, the phase-encoding scheme, the dose of contrast agent concentration and the magnetic field strength can affect the relationship between the changes in the SI and in the concentration of the T1-weighted images (2-5, 9-15). In this work, we aimed to study the effect of TI on the concentration of the contrast agent which leads to a minimum SI using the IR T1-weighted 3-dimensional fast-gradient echo imaging sequence.

Methods

Theory: The MR sequence can influence the connection between T1 and the SI, which in turn is dependent on the concentration of the contrast agent (16). Eq. (1) expresses the standard IR sequence:

$$S(t) = S_0\left(1-(1-\cos\theta_{inv})\exp\frac{-TI}{T1}+\exp\frac{-TR}{T1}\right), \quad (1)$$

where S (t) is the SI after the administration of the contrast agent, and S_0 is the observed SI when no magnetization preparation pre-pulses are applied or there is no contrast agent; θ_{inv} denotes the flip angle of the inversion pulse. If θ_{inv} = 180° in the IR sequences or at the higher concentrations of the contrast agent, Eq. (1) can be written as follows (4, 17,18):

$$S(t) = S_0\left(1-2\exp\frac{-TI}{T1}+\exp\frac{-TR}{T1}\right)\exp\left(-\frac{\mathrm{TE}}{\mathrm{T2}}\right), \quad (2)$$

Eq. (2,) which contains the concentration of the contrast agent at time t (C (t)) can be described as (4):

$$S(t) = S_0\left(\begin{array}{l}1-2\exp\left(-TI\left(\frac{C(t)}{K}+\frac{1}{T1_{Pre}}\right)\right)+\exp\\ \left(-TR\left(\frac{C(t)}{K}+\frac{1}{T1_{Pre}}\right)\right)\end{array}\right)\exp\left(-\frac{\mathrm{TE}}{\mathrm{T2}}\right), \quad (3)$$

where $T1_{Pre}$ is the longitudinal relaxation times before the contrast application; K is a constant that depends on the contrast medium (13, 19).

The null point of a tissue does not have a longitudinal magnetization component and does not produce a signal. Therefore, for the null point of a tissue, S (t) = 0, so:

$$1-2\exp\left(-TI\left(\frac{C(t)}{K}+\frac{1}{T1_{Pre}}\right)\right)=\exp\left(-TR\left(\frac{C(t)}{K}+\frac{1}{T1_{Pre}}\right)\right), \quad (4)$$

$$1-2\exp\left(-TI\left(\frac{C(t)}{K}+\frac{1}{T1_{Pre}}\right)\right)=\exp\left(-TR\left(\frac{C(t)}{K}+\frac{1}{T1_{Pre}}\right)\right). \quad (5)$$

and assuming that TR>>T1, the null point is

$$TI\left(\frac{C(t)}{K}+\frac{1}{T1_{Pre}}\right)=\ln\left(\frac{1}{2}\right)\Rightarrow TI=\left(\frac{0.96}{\frac{C(t)}{K}+\frac{1}{T1_{Pre}}}\right). \quad (6)$$

Or, considering Eq. (2), the null point of a tissue or fluid can be expressed as:

$$1-2\exp\frac{-TI}{T1}=\exp\frac{-TR}{T1} \quad (7)$$

Or,

$$TI = T1 \times \ln(\frac{1}{2}) = 0.693T1. \quad (8)$$

Therefore, TI can be adjusted to optimize the contrast between the suppressed region of interest (e g., tissue) and its surroundings.

Phantom: To assess the effect of different TI values on a concentration that leads to a minimum SI, a phantom was designed with vials containing a variety of concentrations of the contrast agent. The shape of the phantom was approximately cubic and was made of Perspex; its length, width and height were 20, 18 and 20 cm, respectively.

The phantom contained 25 vials (glass tubes, inner diameter approximately 15 mm) and was filled with different concentrations of Gd-DTPA (Magnevist, Schering Health Care Ltd, West Sussex, UK)). The concentration of Gd-DTPA varied between 0 and 19.77 mmol/L (0.00, 0.30, 0.45, 0.60, 0.75, 0.90, 1.20, 1.50, 1.80, 2.10, 2.39, 2.69, 2.99, 3.28, 3.58, 3.98, 4.96, 5.95, 7.93, 9.90, 13.85, and 19.77 mmol/L). A clinical head-and-neck coil was used for the phantom. The vials were set vertically, and the axes of the vials were perpendicular to the image plane (coronal image). We assumed that the different parts of the coil provided a uniform SI.

Fig. 1 displays a coronal image of the phantom with different concentrations of the contrast agent.

Image Acquisition: The phantom was situated within the coil. All studies were performed on a 1.5 T clinical MR scanner (Vision, Siemens Medical, Erhlangen, Germany). We used IR T1-weighted 3-dimensional fast gradient echo images to measure the SI in vials with varying concentrations of the contrast agent.

The imaging parameters were as follows:

Matrix size = 256×256, TR = 5000 ms, TE = 3 ms, TI was varied between 100 and 3000 ms (100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 1000, 1200, 1500, 2000, 2500, and 3000 ms), pixel size = 1×1 mm, slice thickness = 10 mm, and flip angle = 15°. Each image was repeated 16 times.

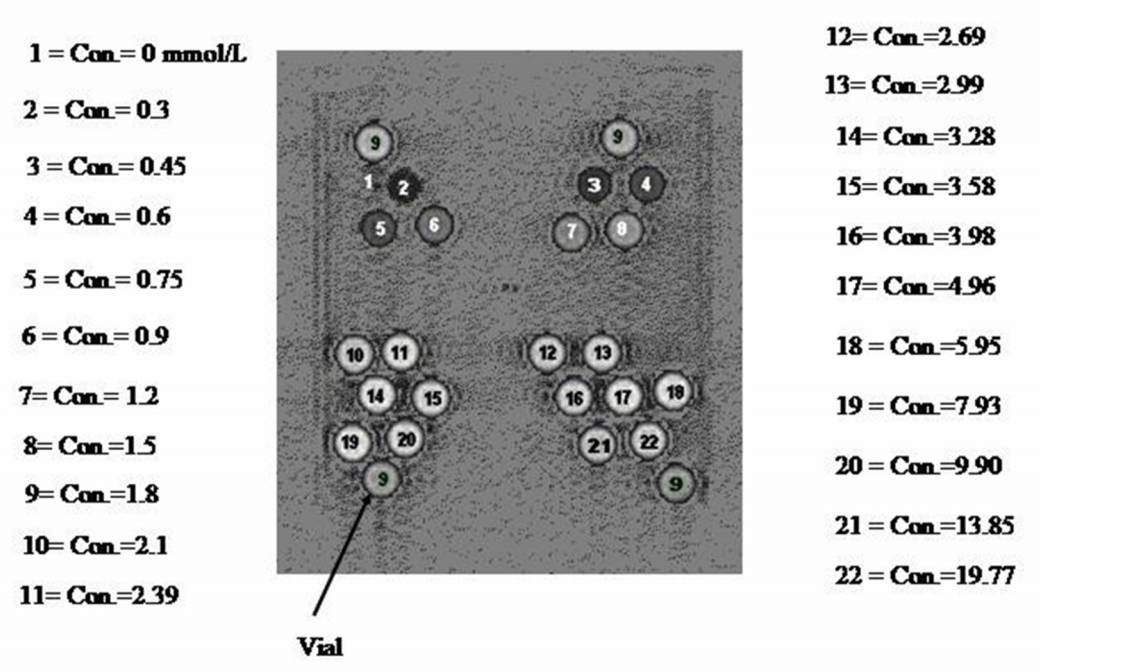

Fig.1. The coronal image of the phantom is shown in Figure 1, and the position of different concentrations (mmol/L) inside the vials can be seen in this figure.

Image Analysis: The images were processed by the transfer of the image data from the MR scanner to a personal computer, and they were then computerized by an image-processing software in an interactive data language (IDL, Research Systems, Inc.; http://www.rsinc.com).

Programs were written to find the followings automatically:

1. The mean image of 16 acquisitions primarily used for the improvement of the signal-to-noise ratio.
2. The mean SI and standard deviation of the 9 innermost pixels of the vial to avoid the partial volume effects.
3. The concentration at which SI is minimized.

These programs can be run on either a UNIX workstation or a personal computer.

Results

Figs. 2-8 demonstrate some typical results for the mean SI from the 9 innermost pixels of the vials versus the concentration of the contrast agent at TI values of 100, 300, 500, 700, 1000, 2000 and 3000 ms, respectively.

Fig. 9 shows that the minimum SI was obtained at different concentrations to obtain different values of TI.

Fig. 10 shows the minimum SI versus TI. The figure indicates that the minimum SI was nearly the same, and the slope of the curve was low at lower TI values. At higher TI (more than 1500 ms), the minimum SI would increase, and the slope of the curve would be very high.

The figures show that the T1-shortening effect is dominant at the low concentrations of Gd-DTPA based on Eq. (1), whereas the T2-shortening effect is dominant at high concentrations and leads to a decrease in SI (see

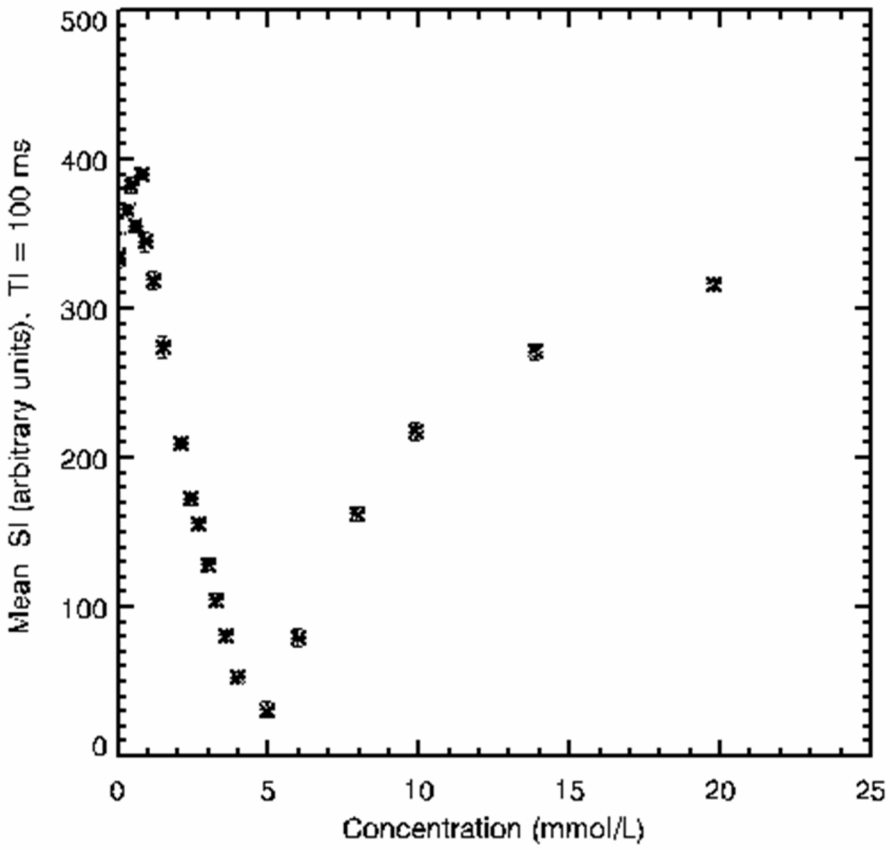

Fig. 2. Demonstrates the concentration of the contrast agent versus the mean SI from the 9 innermost pixels of the vials at TI = 100 ms. A minimum SI appeared at a the concentration of 4.96 mmol/L. The error bars demonstrate the standard deviation for each vial.

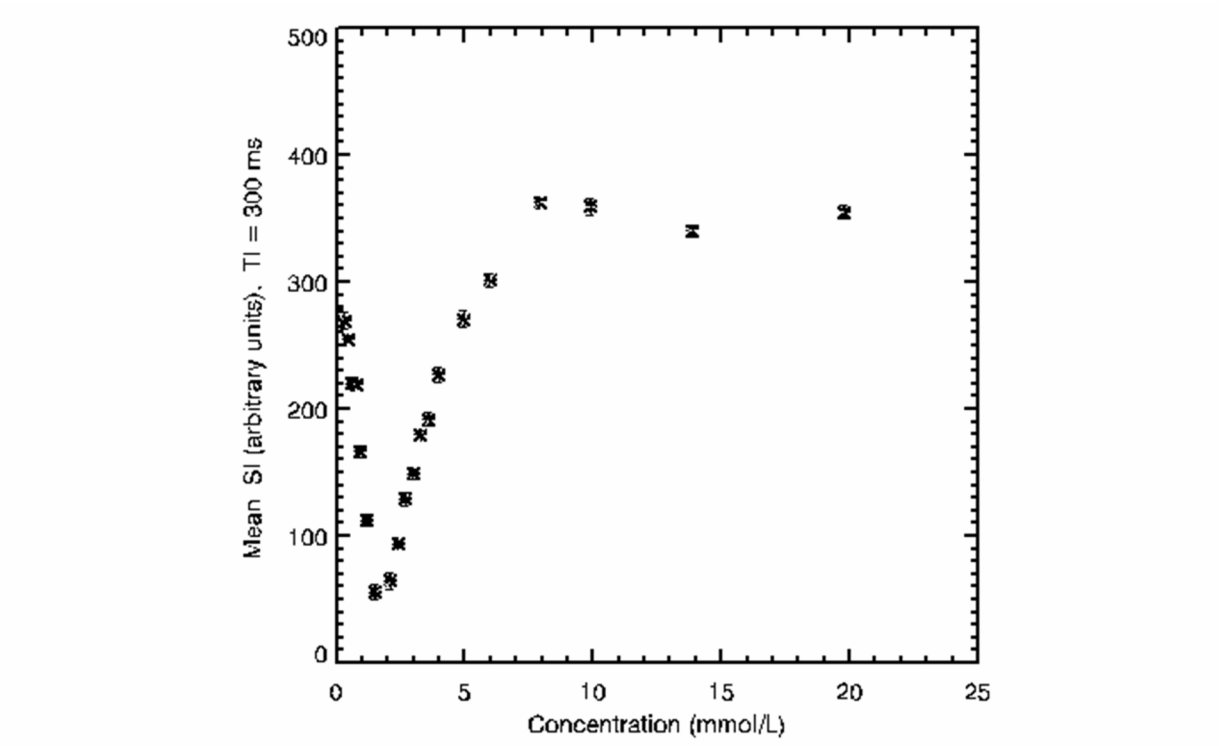

Fig. 3. Displays the concentration of the contrast agent versus the mean SI from the 9 innermost pixels of the vials at TI = 300 ms. A minimum SI appeared at the concentration of 1.55 mmol/L. The error bars displayed the standard deviation of each vial.

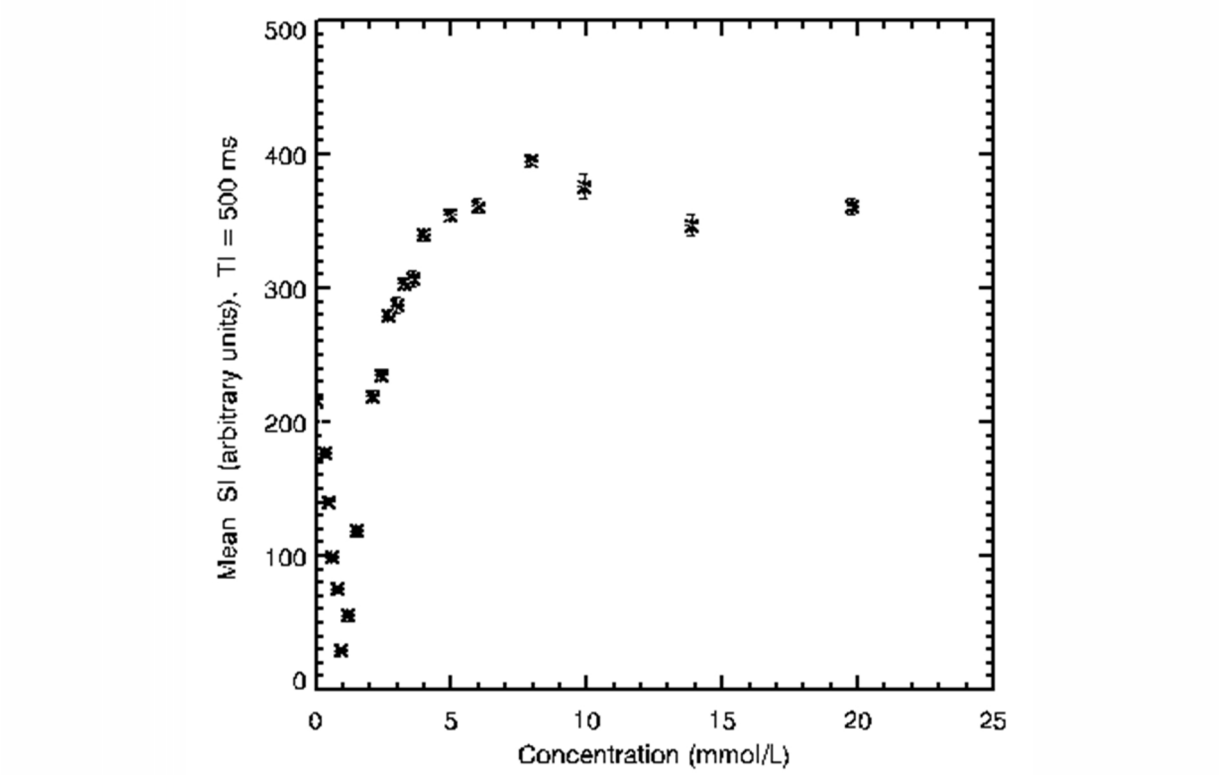

Fig. 4. Shows the concentration of the contrast agent versus the mean SI from the 9 innermost pixels of the vials at TI = 500 ms. A minimum SI appeared at the concentration of 0.9 mmol/L. The error bars show the standard deviation for each vial.

Eq. (3)).

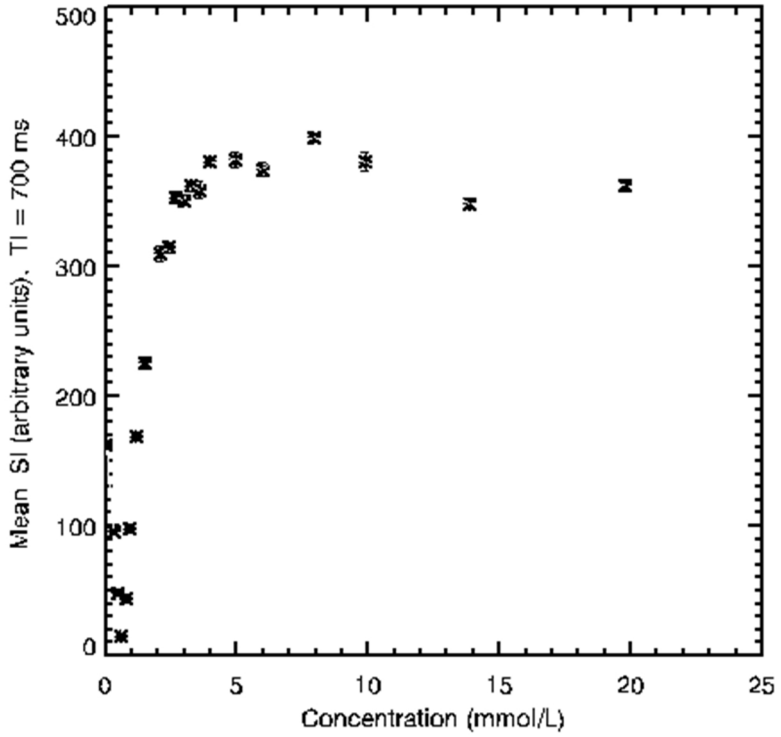

Fig. 5. Exhibits the concentration of the contrast agent versus the mean SI from the 9 innermost pixels of the vials at TI = 700 ms. A minimum SI appeared at the concentration of 0.6 mmol/L. The error bars display the standard deviation for each vial.

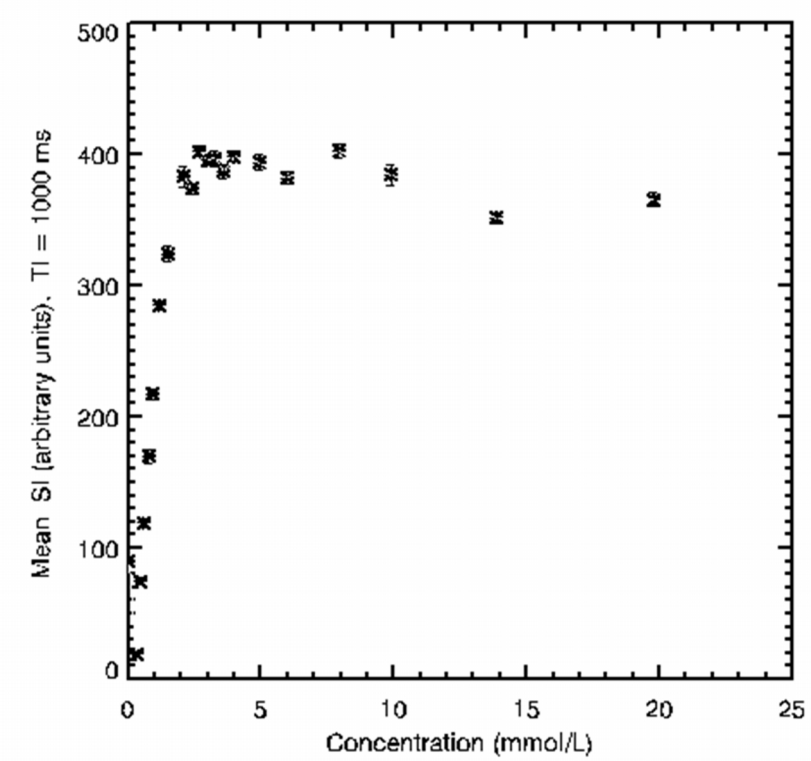

Fig. 6. Demonstrates the concentration of the contrast agent versus the mean SI from the 9 innermost pixels of the vials at TI = 1000 ms. A minimum SI appeared at the concentration of 0.3 mmol/L. The error bars showed the standard deviation for each vial.

Discussion

The IR sequences will be started with a 180-degree inversion radiofrequency pulse, and the pulse will flip the longitudinal

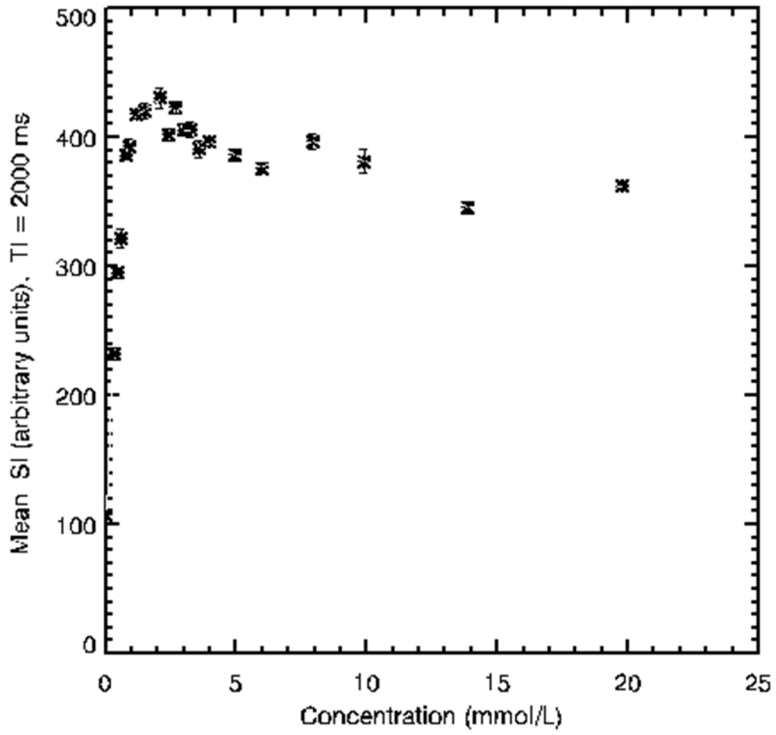

Fig. 7. Shows the concentration of the contrast agent versus the mean SI from the 9 innermost pixels of the vials at TI = 2000 ms. A minimum SI appeared at the concentration of 0.0 mmol/L. The error bars demonstrate the standard deviation for each vial.

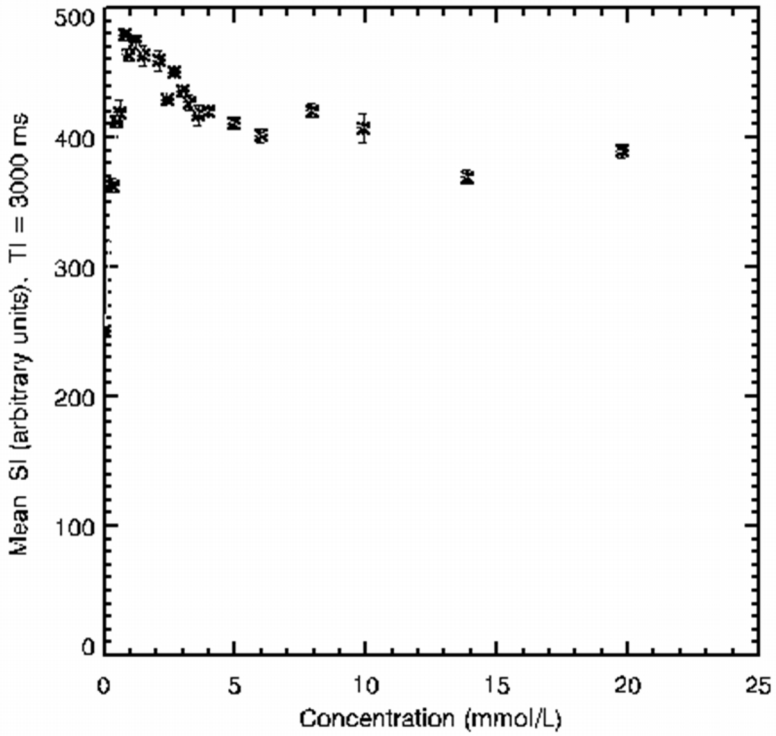

Fig. 8. Demonstrates the concentration of the contrast agent versus the mean SI from the 9 innermost pixels of the vials at TI = 3000 ms. A minimum SI appeared at the concentration of 0.0 mmol/L. The error bars showed the standard deviation for each vial.

magnetization vector through the x-y plane and into the z- direction. The longitudinal magnetization gradually increases after the external inversion pulse is turned off; this is

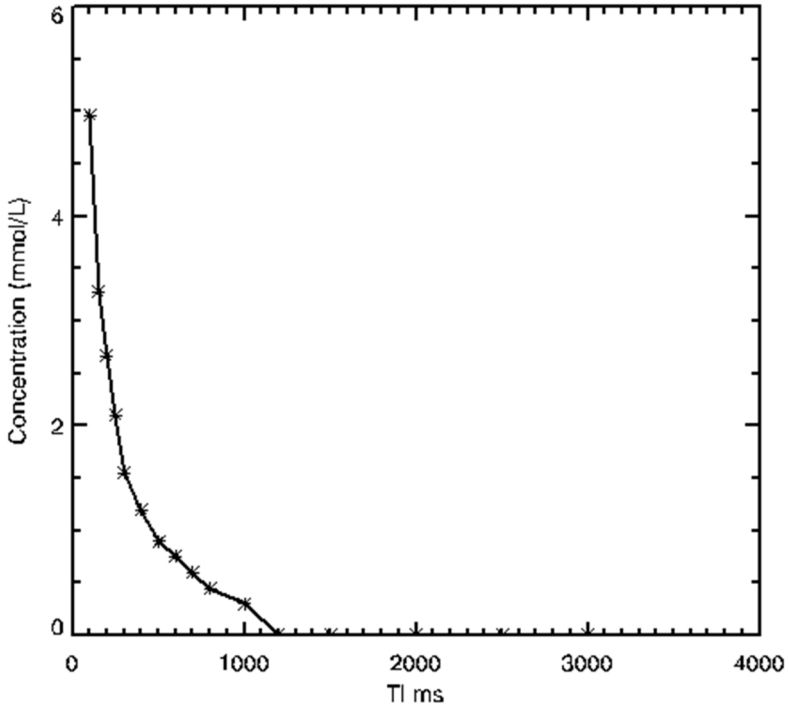

Fig. 9. Exhibits TI versus the concentration of the contrast; a concentration which leads to a minimum SI will be decreased when TI is increased; the concentration vanishes to zero at higher TI (more than 1200 ms).

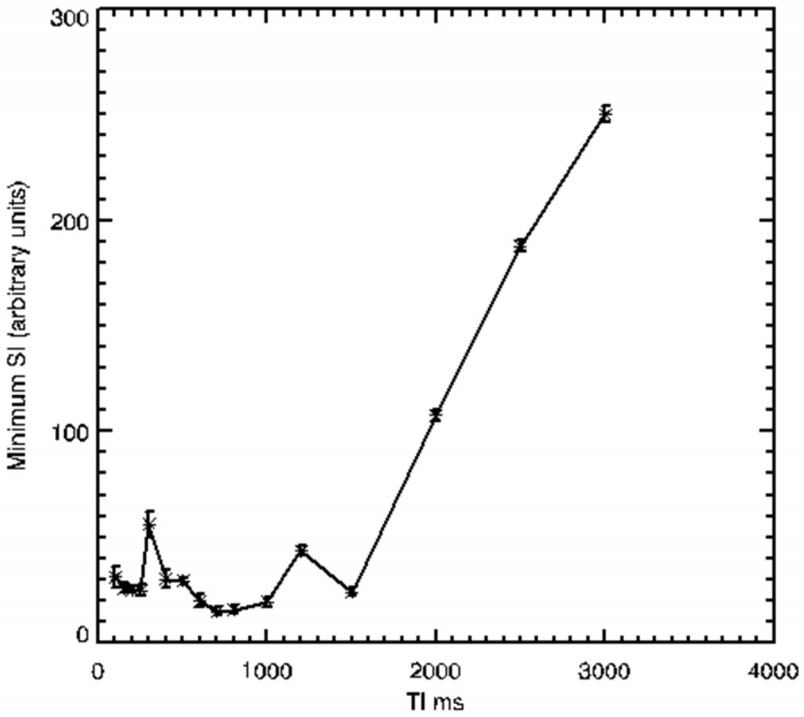

Fig. 10. Displays TI versus minimum SI. The SI is increased at higher TI.

called T1 recovery. The reconstruction process in IR images is only sensitive to the magnitude of the magnetization of a tissue, not whether it is positive or negative. The positive or negative magnetization values depend on the TI and tissue T1 values and

also on the time at which the readout sequence is applied. Therefore, the image contrast is dependent on the TI value for a specific tissue when other image parameters are constant (6).

Bydder et al. (20) stated that a short TI (80-180 ms) can be used for the null SI for fat, white matter and liver. The sign of the longitudinal magnetization is negative for these tissues. In addition, they reported that a medium TI (200-800 ms) and a long TI (1600-2800 ms) are suitable for nulling of blood and CSF, respectively. The sign of longitudinal magnetization is mixed negative and positive for blood and positive for CSF.

Amano et al. (21) investigated the differences in null points between the left ventricle (LV) and right ventricle (RV) in patients with cardiac disease using a contrast-enhanced inversion recovery MR imaging. They reported that the null points of the RV myocardium were shorter than those of the LV myocardium in some patients with cardiac disease.

Nakamura et al. (22) investigated the effect of TI values (100, 200, 300, 400, and 500 ms) to differentiate the fine structures in the brain's gray and white matter (gray-gray and white-white differentiation). They reported that a TI of 400 ms was the most suitable for this purpose.

Wagner et al. (23) investigated the influence of TI on acute myocardial infarct size measurements and the difference in image intensities between the infarcted and normal myocardium based on MRI delayed contrast enhancement. They found that TI has an effect on the image intensity and should be chosen very prudently.

In clinical studies, normally TI= 800ms will be used in IR T1-weighted Turbo Fast Low Angle Shot (Turbo FLASH) images because of the null signal from the blood (24).

The results of this study revealed that the T1 recovery curve did not cross the x- axis for TIs of 100-1000 ms; a minimum SI can be seen in Figs. 2-5.

Furthermore, the findings of this study demonstrated that (Fig. 9 and 10) the concentration of the contrast agent, which leads to a minimum SI, is dependent on TI and that the minimum SI will be increased at higher TI.

The results of this study also revealed that the T1 effect, which leads to an increased SI, will appear at lower TI at different concentrations. In addition, the T2 effect, which leads to a decrease in SI, will appear from TI = 250 ms at higher concentrations.

According to the results, the range of TI is an important parameter for measuring SI. TI can have an effect on the concentration of the contrast agent, which leads to a minimum SI. Therefore, when using an IR sequence with a high signal-to-noise ratio or when suppressing SI on an image, the image parameters such as TI should be chosen with great caution.

Conclusion

The effect of TI on the SI of IR T1-weighted images was evaluated in this study. The result of this study revealed that a difference in TI can have an effect on the strength of the SI, which is dependent on the concentration of the contrast agent. In conclusion, to suppress the SI of specified tissues in clinical studies (e.g., fat suppression or blood suppression in perfusion measurements), the TI parameter should be chosen very cautiously.

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