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Evaluation of Selective Saturation and Refocusing Pulses in Chemical Shift NMR Imaging

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Abstract: There are several methods to achieve selective NMR image of differing chemical species with the three most popular methods of Dixon's, CHESS, and SECSI. A major problem common to all chemical shift imaging methods is the uniformity of the static magnetic field and distortions introduced when RF coils are loaded with a conducting specimen. Without magnetic field shimming, these methods cannot be used to acquire selectively image protons in fat and water which are separated by approximately 3.0ppm. Experiments with a phantom, with linewidths of 2.5 to 3.5ppm, were quantitatively evaluated for the three methods and a new chemical shift imaging method. In this study the new chemical shift imaging method (modified CHESS+SECSI technique) which included a selective saturation and refocusing pulse, was developed to determine the ratios of water and fat in different samples.

INTRODUCTION

In normal NMR imaging of hydrogen, the different resonance frequencies of water and fat produce artifacts at the tissue boundaries. If the frequency or chemical shifts are in opposite directions, the signal due to fat will shift away from that of water. The typical result of such an effect is to produce a bright rim on one side of a tissue where the fat and water resonances overlap and a dark rim on the other side where they separate. Since the frequency is proportional to field strength, this artifact becomes greater at higher fields. With specific RF pulse techniques, chemical shift effects can be used to produce separate water and fat images.

This study attempts to provide the theoretical principles of chemical shift NMR imaging. To date, most chemical shift imaging techniques have not been quantitatively evaluated. We quantitatively evaluated three common RF pulse sequences (Dixon's method, CHESS method, SECSI method) for chemical shift imaging. In addition, a new chemical

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shift imaging method (modified CHESS + SECSI technique) which include a selective saturation and refocusing pulse, was developed to determine the ratios of water and fat in different samples (Mayonnaise, Propylene Glycol, Mineral Oil, Water)

METHOD AND EXPERIMENTAL

There have been several methods developed to achieve selective NMR of various chemical species. Brown and coworkers[1] were the first to suggest that the MRI could obtain both chemical and spatial information from a single pulse sequence; however, this method is rarely used because of the long time required for scanning and will not be considered here.

The Modified Bloch Equations for Chemical Exchange

In the case of two nuclei which periodically exchange their chemical environment and thus their Larmor frequencies, the Bloch Equations[2] for NMR line shape calculations are modified. This is done most easily by defining a complex magnetization,

$$G = M_{x'} + iM_{y'} \qquad [1]$$

and then combining this complex magnetization into equations

$$\begin{aligned} dM_{z'}/dt &= \gamma[M_{x'}B_{y'} - M_{y'}B_{x'}] - (M_{z'} - M_o)/T_1 \\ dM_{x'}/dt &= \gamma[M_{y'}B_{z'} - M_{z'}B_{y'}] - M_{x'}/T_2 \\ dM_{y'}/dt &= \gamma[M_{z'}B_{x'} - M_{x'}B_{z'}] - M_{y'}/T_2 \end{aligned} \qquad [2]$$

If one assumes that M_z M_0, allowable for weak B_1 fields, the Bloch equation becomes

$$\begin{aligned} dG/dt &= i(\omega_0 - \omega)G - i\gamma B_1 M_0 - G/T_2 \\ dM_z/dt &= \gamma B_1 M_{y'} - (M_z - M_0)/T_1 \end{aligned} \qquad [3]$$

In the absence of exchange between the A and B positions, and with resonance frequencies ω_A and ω_B, then

$$\begin{aligned} dG_A/dt + \alpha_A G_A &= -i\gamma B_1 M_{0A} \\ dG_B/dt + \alpha_B G_B &= i\gamma B_1 M_{0B} \end{aligned} \qquad [4]$$

where, $\alpha_A = 1/T_{2A} - i(\omega_A - \omega)$, $\alpha_B = 1/T_{2B} - i(\omega_B - \omega)$

At equilibrium, magnetization is transferred from A to B and back to A. If nuclear precession is ignored during the transitions from A to B and from B to A, equation [4] can be extended as follows :

$$dG_A/dt + \alpha_A G_A = -i\gamma B_1 M_{0A} + G_B/\tau_B - G_A/\tau_A$$
$$dG_B/dt + \alpha_B G_B = i\gamma B_1 M_{0B} + G_A/\tau_A - G_B/\tau_B \qquad [5]$$

Here, the quantities $1/\tau_A = k_A$ and $1/\tau_B = k_B$ denote the probability that a nucleus undergoes a transition from A to B or from B to A.

For adiabatic passage during a reaction, a stationary state is assumed (i.e., $dG_A/dt = dG_B/dt = 0$). With $M_{0A} = p_A M_0$ and $M_{0B} = p_B M_0$, one obtains

$$G = G_A + G_B$$
$$= -i\gamma B_1 M_0[\tau_A + \tau_B + \tau_A\tau_B(\alpha_A p_B + \alpha_B p_A)]/[(1 + \alpha_A p_A)(1 + \alpha_B p_B) - 1] \qquad [6]$$

where τ_A and τ_B are the average life times of the nuclei in positions A and B, and p_A and p_B are the molar fraction of components A and B, respectively. This equation contains the real and the imaginary parts of the magnetization. To calculate the absorption signal, the imaginary part of Eq.[1] must be separated by solving Eq.[6]. In this case one obtains the equation for the line shape, $g(\nu)$, of the resonance signal[3]

$$g(\nu) = [(1 + \tau\pi\Delta)P + QR] / (4\pi^2 P^2 + R^2) \qquad [7]$$

where $P = (\Delta^2/4 - \nu^2 + \delta\nu^2)\tau + \Delta/4\pi$

$Q = [-\nu - (p_A - p_B)\delta\nu]\tau$

$R = 0.5(p_A - p_B)\delta\nu - \nu(1 + 2\pi\tau\Delta)$

and τ represents $\tau_A\tau_B/(\tau_A + \tau_B)$, $\delta\nu = \nu_A - \nu_B$ and Δ is the width at half-height of the signal.

Recently Yamamoto and Kohno[4] introduced a method which resolved two chemical shift images into real and imaginary components, where for simplification $1/T_{2A}$ was assumed equal to $1/T_{2B}$ in Eq.[4].

Chemical Shift Imaging Techniques

(a) Dixon's Method

Dixon[5], Sepponen[6], Mitchell[7], and others developed methods in which spectral information is obtained from spin-echo sequences by acquiring two separate images at different phases of the π pulse. Two data sets are acquired, the first in-phase set having two different proton spectral components of equal phase, and the second out-of-phase set having spectral components of opposite phase. Addition or subtraction of the two set will produce either a pure water or fat image. The timing diagram for the pulse sequence used by Dixon is indicated in Figure 1.a, in which the difference in acquisition of the two data sets involve only a relative shift of the π inverting pulse. The spin-echo sequence is modified by changing the duration of the π pulse, however the signal is sampled in the same manner. In an ordinary spin-echo sequence, the application of a slice selective z-gradient during the $\pi/2$ pulse produces a frequency difference between excited fat and water slices. This is in addition to the normal chemical shift effects. If the π pulse is shifted by a time τ, so that the Hahn echo is displaced from the z-gradient pulse by a time 2τ, the phase of a processing proton will be altered. If 2τ is short enough, phase coherence will be retained, and sufficient NMR signal can be obtained. In this binary spectrum, the two components can be approximated by spectral lines arising from water protons, with a mean resonance angular frequency ω_0, and aliphatic(fat) protons with a mean resonance frequency $\omega_0 - \Delta\omega$. The average chemical shift $\Delta\omega$ of the aliphatic protons from water is about 3.5 ppm.

(b) *CHESS method*

An alternative approach, used in Chemical Shift Selective (CHESS) imaging[8,9], is to add selective frequency saturation $\pi/2$ pulse for one of the spectral components. This method was developed from certain spectroscopy techniques which use soft pulse at specific frequencies in order to saturate a spectral line or group of lines whose contribution is not desired. In the CHESS technique, shown in Figure 1.b, a selective saturation pulse, XW3, is applied whose purpose is to provide a 90 flip angle to the undesired spins. Since spins are affected by both $\pi/2$ and π pulses in a standard spin-echo technique, only one of the rf pulses is necessary to be spatially selective in order to excite only the longitudinal component of the magnetization vector. A chemical shift selective pulse can be substituted for one of these two pulses to produce results similar to the CHESS technique. The length of the saturation pulse is determined by the separation of the resonance frequencies of each chemical component in the desired volume, by the separation of the resonance frequencies of each chemical component in the desired volume, by the rf pulse shape, and by the spectral width of each component. Since only one component is saturated, all others contribute to the image.

(c) *SECSI method*

The Selective Echo Chemical Shift imaging (SECSI) technique was proposed by Joseph.[10,11] In this technique, spectral selectivity is obtained using a modified spin-echo process, where the rf pulse is designed so that only the desired spectral line is refocussed, and essentially there is complete elimination of all other spectral lines. This method also requirers a high degree of homogeneity of the main field in order that the spectral lines can be resolved. The SECSI pulse sequence, diagrammed in Figure 1.c, contains no saturation pulse, however the width of the sinc refocussing π pulse, XW1, is increased in order to be frequency selective. The theory of this process, for the case of a perfect π pulse, has been described.[10]

(d) *Selective Saturation and Refocusing Pulse method*

The selective saturation and refocusing pulse method developed here is a combination of the CHESS and SECSI methods. In this technique as shown in Figure 1.d, a saturation pulse was used for either the fat or water resonance along with a sinc refocusing π pulse tuned to null the undesired chemical shift component.

MRI Experiments

The experiments were performed on a horizontal 2.0*Tesla*, 31*cm* small bore superconducting magnet and gradient subsystem interfaced to modified Technicare rf electronics (Oxford Instruments). The RF coil was a 15*cm* diameter birdcage resonator. Normal spin-echo sequences were modified to produce the four chemical shift methods on a PDP 11/84 computer system.

Initial experiments using phantoms were performed using the four methods under conditions of poor B_o homogeneity, *i.e.*, no magnetic field shimming was performed and water linewidths were approximately 3.0 *ppm*. This phantom consisted of a sphere, inner-diameter 35 *mm*, filled with mineral oil and Mn-dissolved water. Axial scans were performed using a TR = 500*msec*, TE = 35*msec*, and a slice thickness of 2*mm*.

Secondly, the new chemical shift method which included a selective saturation and refocusing pulse, was used to determine the ratios of water and fat in different samples. The samples were four tubes, inner-diameter 10*mm*, containing mineral oil, water, propylene glycol in distilled water, and mayonnaise.

RESULTS AND DISCUSSION

In Figure 2 and Figure 3, the NMR images are given; (a) Dixon's method, which is less susceptible to field homogeneity than other methods; however, has a lower fat (or water) suppression ratio; (b) the CHESS method, where the effects of magnetic field inhomogeneity are shown as only a partial suppression of water and fat resonances; (c) the SECSI method, which shows good delineation between water and fat except at the lower edge of the phantom due to the effects of field inhomogeneity; and (d) the modified CHESS +SECSI method, which gave the best results on our system under the same scanning conditions. Also the S/N of method four was approximately 3 times higher than that obtained using the SECSI technique as Table 1.

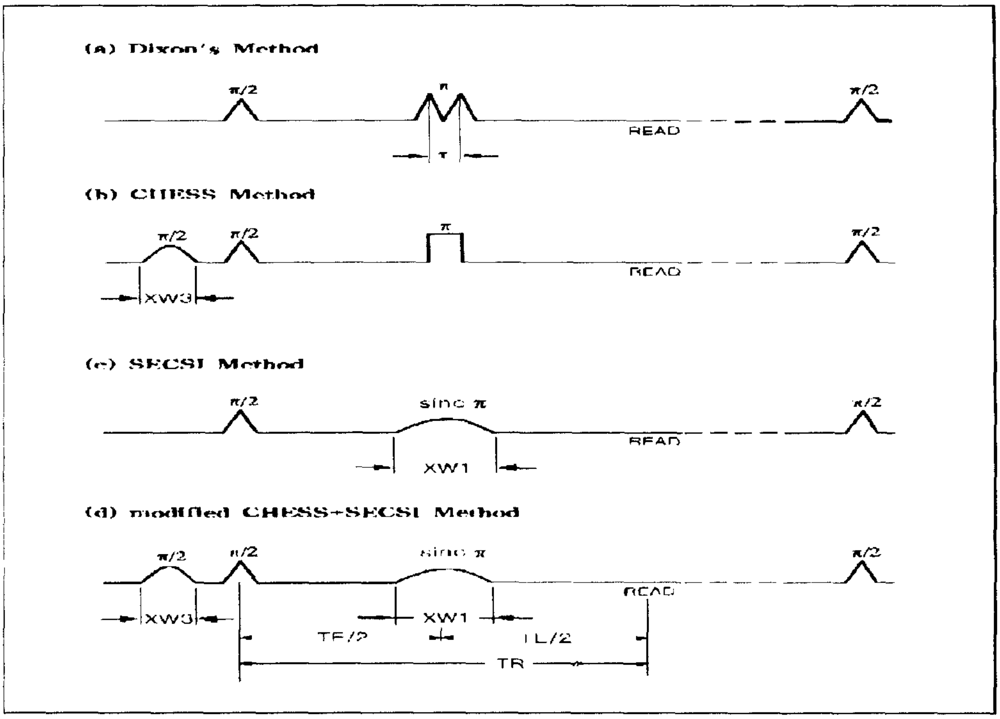
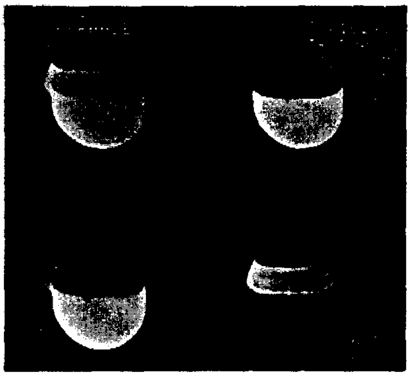


Fig. 1. RF pulse sequences for chemical shift imaging : (a) Dixon's method, (b) CHESS method, (c) SECSI method, (d) modified CHESS + SECSI method

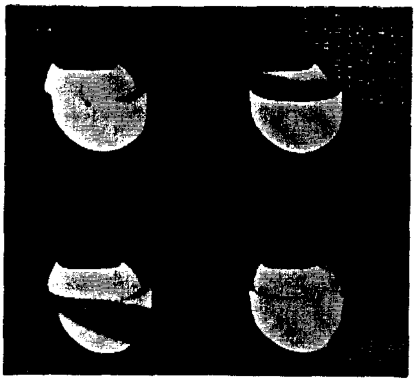
Table 1. Suppression ratios (water and fat images)

Sequence	Sequence	CHESS	SECSI	Modified CHESS+SECSI
W/F	1.070	8.461	14.729	36.998
F/W	6.465	6.926	17.051	38.258

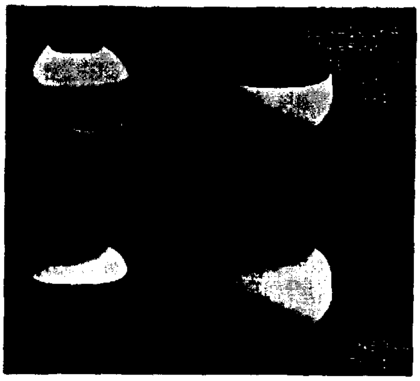
Figure 4 shows that water and fat images are clearly resolved by a modified CHESS + SECSI method. In the image using a normal spin-echo sequence (a), the composition of the water/fat cannot be obtained. Using a modified CHESS + SECSI method, the composition ratio of fat and water can be resolved from the fat (b) and water image (c). In addition to the chemical shift images, a conventional density image (d) can be easily obtained by superimposing the two images (b) and (c). Using these results, the



(a) Dixon's method images :
(UL) in-phase (UR) Out-of-phase
(LL) water (LR) fat



(b) CHESS method images :
(UL) normal (UR) water
(LL) fat (LR) water+fat



(c) SECSI method images :
(UL) normal (UR) water
(LL) fat (LR) water+fat

(d) modified CHESS+ SECSI images
(UL) normal (UR) water
(LL) fat (LR) water+fat

Fig. 2. Chemical shift images (water and fat in one phantom)

composition ratio is compared with those determined from the normal spin-echo sequence and modified CHESS+SECSI sequence as Table 2.

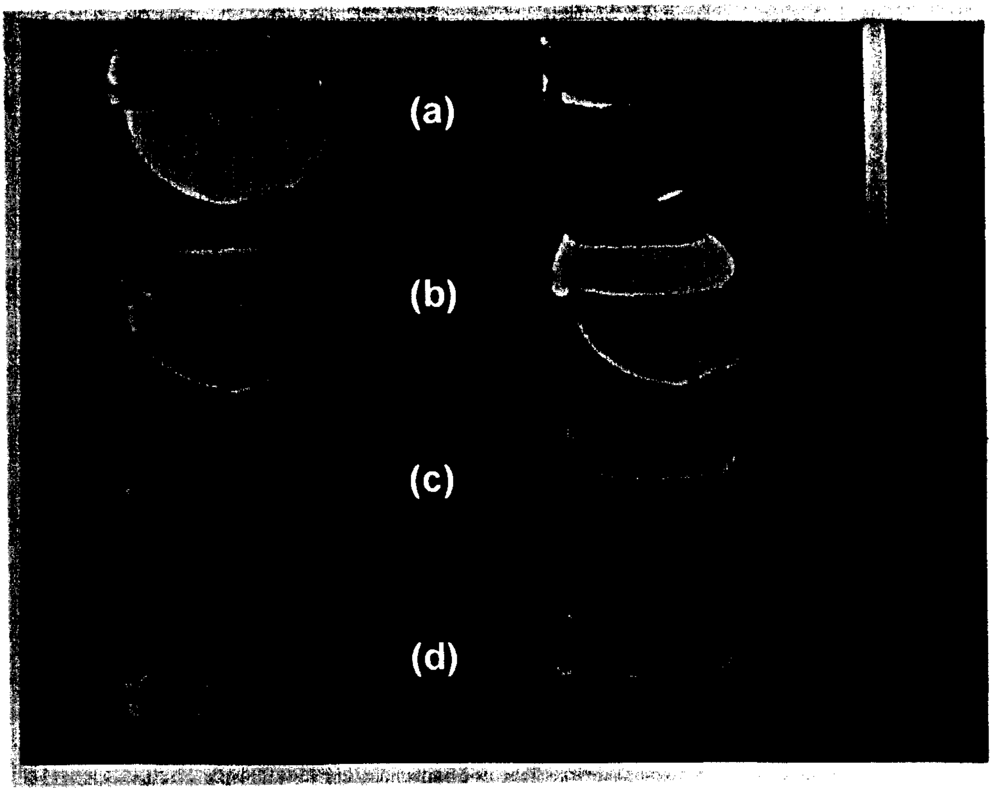


Fig. 3. Chemical shift images for water and fat in one phantom : (a) Dixon's method, (b) CHESS method, (c) SECSI method, (d) modified CHESS+SECSI method (left : water, right : fat)

Table 2. Composition ratio of sample images

SAMPLE	Normal Spin-Echo		Normal Spin-Echo	
	S/N	Signal (R)	Water (R)	Fat (R)
Mineral oil	9.447	0.149	0.001	0.999
Water	47.083	0.740	0.986	0.014
Porpylene glycol	63.616	1.000	0.367	0.633
Mayonnaise	62.196	0.978	0.597	0.403

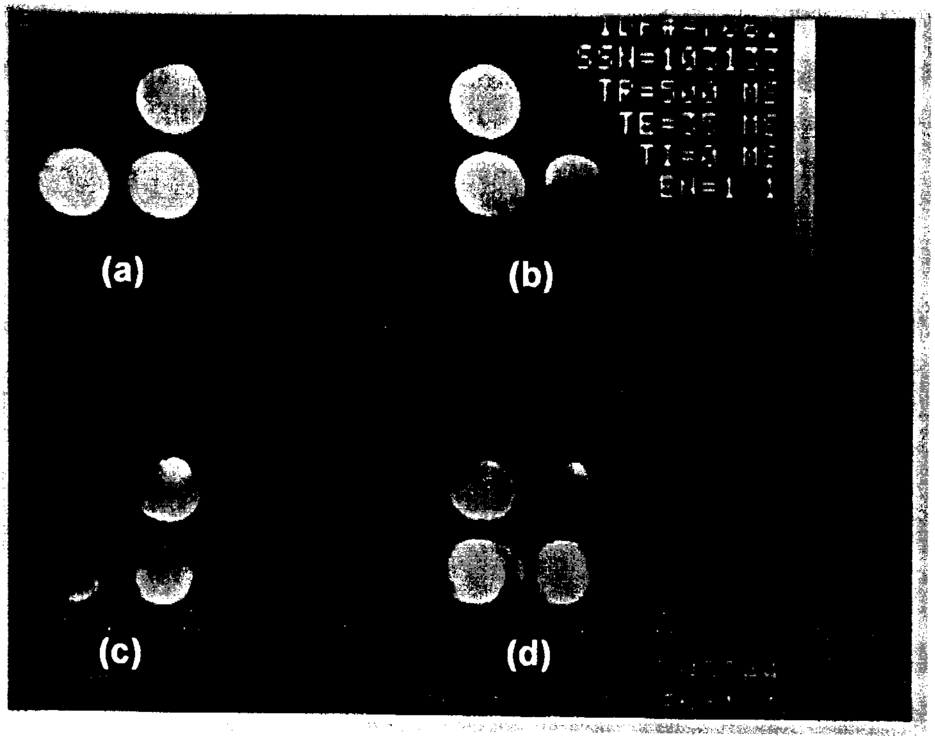


Fig. 4. Chemical shift images by modified CHESS + SECSI method ; IMAGES (a) normal image, (b) fat image, (c) water image, (d) fat + water image : Phantoms in each imges indicate mineral oil (UL), water (UR), propylene glycol (LL), mayonnaise (LR)

CONCLUSION

The advantage of Dixon's method is that there is little susceptibility to magnetic field inhomogeneities and is readily implemented with only a slight modification of the standard spin-echo sequence. However, if the spectrum has more than two components, or if an incorrect time delay, τ , is used during data acquisition, then the Dixon's method fails to provide quantitative indices of fat/water content and may lead to incorrect interpretations. Also, since this method requires two separate acquisition to distinguish between fat and water, motion between scans will produce erroneous results, such as in the interpretation of certain bone pathologies.

The CHESS technique has the advantage in that it is readily adaptable to produce suppression of any group of lines using only one acquisition. However, this technique requires good magnetic field homogeneity so that various spectral lines within the desired imaging volume can be resolved.

While an undesired chemical component can be suppressed and other frequency components may be imaged by the CHESS method, only a single desired frequency is selected for SECSI imaging. Therefore, for binary system, like fat and water, only one desired component can be imaged. However, imaging of more than two frequency components would be different, since all components except saturated components can be imaged in the CHESS method and only the selected component among the chemical components can be imaged in the SECSI technique.

A major problem common to all chemical shift imaging methods is static magnetic field non-uniformity and distortions introduced when rf coils are loaded with a conducting specimen. The CHESS method and SECSI method are very sensitive to field homogeneity. The modified CHESS + SECSI (Selective Saturation and Refocusing Pulse Technique) demonstrated superior results even without field shimming.

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