CHEMICAL SHIFT IMAGING

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Abstract

Lipid component and water component image in living organism can be acquired due to its chemical shift difference. Various techniques for chemical shift imaging were used for acquiring separated image. It is necessary two imaging experiments to acquire two separated images with Dixon's method. This technique is less susceptible to local magnetic inhomogeneities and easily applied to multi-slice imaging. With CHESS and SECSI method, which based on chemical selectivity of R.F. pusle, either water or lipid image can be acquired by one imaging experiment. However, those are more susceptible to local magnetic field inhomogeneities and difficult to apply to multi-slice imaging. The SECSI method showed best signal suppression ratio of fat and water, which is measure of separation of water and fat.

요 약

화학적 이동성을 이용하여, 생체의 경우 지방질의 영상 혹은 물성분의 영상을 얻을 수 있다. 여러가지 기술을 사용하여 분리된 성분의 자기공명 영상을 얻었다. Dixon의 방법은 두번의 영상실험을 하여 지방질 영상과 물성분 영상을 구분할 수 있으며, 부분적 자기장의 불균질성에 영향을 적게 받고 다층 영상법에 용이하게 적용할 수 있다. CHESS와 SECSI 방법은 한번의 영상실험으로 물 또는 지방질 영상을 획득할 수 있다. 그러나 부분적 자기장의 불균질성에 영향을 많이 받으며, 다층영상법에 적용하기에는 어려운 점이 있다. 화학 성분의, 즉 지방질과 물성분의 분리의 척도가 되는 지방질 신호대 물성분신호 비에 있어 SECSI 방법이 가장 우수함을 보였다.

1. Introduction

Since the atomic nucleus is surrounded by electrons, the nuclear magnetic moment interacts not only with the applied field, B_o, but also with local magnetic field produced by neighboring electron motion. The motion of electrons is restricted by the molecular structure and its orientation relative to the applied magnetic field and molecular structure. Thus, the field seen by the nucleus is the sum of an externally applied field and a local field generated by the surrounding electrons.

$$H_{nucleus} = H_o + H_{local} = (1-\sigma)H_o \qquad (1)$$

where $H_{local} = \sigma \cdot H_o$ and shielding factor, σ, is in general a second-rank tensor which reflects the orientational dependence. However, for molecules in rapid motion such as in liquid and biological soft tissue, the anisotropic part of shielding factor is averaged out and is treated as a scalar quantity.

The water proton resonance peak is normally used as reference for biological and medical applications in proton MR spectroscopy and imaging because all biological samples have high water concentration. Tetra-methyl-silane (TMS) is generally the accepted reference for chemical application of proton MR spectroscopy. The resonance peak frequencies of sample, ν_s, and reference, ν_r, are expressed as

$$\nu_s = \frac{\gamma}{2\pi} H_o(1-\sigma_s) \qquad (2)$$

$$\nu_r = \frac{\gamma}{2\pi} H_o(1-\sigma_r) \qquad (3)$$

The chemical shift, δ, on a dimensionless scale is defined as

$$\begin{aligned}\delta &= \frac{\nu_r - \nu_s}{\nu_r} \times 10^6 \ ppm \\ &= \frac{\sigma_r - \sigma_s}{1-\sigma_r} \times 10^6 \ ppm \\ &\simeq (\sigma_r - \sigma_s) \times 10^6 \ ppm\end{aligned} \qquad (4)$$

and the shielding factor, σ, is usually much smaller than 1. The chemical shift of the proton resonance peak is expressed in δ ppm relative to a reference peak in spectroscopy because it can be expressed in independent quantity from magnetic field intensity or frequency.

In normal spin echo imaging, the chemical shift causes a displacement in the spatial position of a sample in the frequency encoding direction. The number of pixels displaced, Δn, in the image, can be calculated as

$$\Delta n = \frac{\delta - \nu_r}{\Delta f_{pixel}} \qquad (5)$$

where Δf_{pixel} is a bandwidth of each pixel, and

$$\Delta f_{pixel} = \frac{Number\ of\ samples}{Sampling\ interval} \qquad (6)$$

Several pulse techniques have been developed to measure the chemical shift components of $-CH_3$, $-CH_2$ lipids. Quantifying the aliphatic fat component from biological tissue has been implemented using 3D chemical shift technique by Rosen and Pykett[1] and by a phase-contrast method by Dixon[2]. The 3D method contains the spectral information in the third dimension with the normal spatial information in the other two dimensions. For each spectrum, n^2 sequences are needed for an n by n array. Thus, this method is very time consuming and also suffers from stringent requirement on experimental parameters, such as field homogeneity. In contrast, Dixon's method (DM) is less analytical and less stringent on experimental parameters, but needs at least two experiments for interpretation. However, the DM is less susceptible to magnetic field inhomogeneities and is readily implemented with only a slight modification of the standard spin-echo sequence. The total imaging time is only twice a standard spin echo sequence. Since two data sets are acquired, one sequence involves an in-phase data, which is a spin echo signal for two different proton spectral components with same phase. The second is an out-of-phase data set with the signal of opposite phase. By addition or subtraction of the two images, a water or fat image can be obtained(Fig.1). Since water or fat only images are the subject of clinical interest, several r.f. techniques have been developed for suppressing one of the proton spectral component using selective r.f. pulses. The Chemically Selective Saturation (CHESS) technique[3] utilizes an inversion recovery(IR) pulse to saturate one of the proton spectral components, followed by a normal spin echo image for the non-saturated component. A modified CHESS technique uses different frequencies for the IR pulse and spin echo pulses. The SECSI technique[4] utilizes a selective π pulse to selectively refocus one of the frequency components while other component is not being refocused.

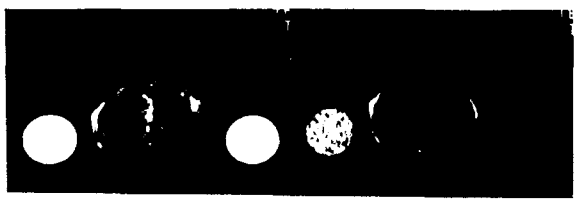

Fig.1 Mouse axial images with Mayonnaise(left) and water(right) vial. Left image is a water wighted and right is a fat weighted image. TR=500msec, TE=33msec

2. Experiments

Dixon's Method:

In a conventional spin-echo sequence, the π pulse is located exactly at the center of the echo time, T_E, so that all the dephased spins with different frequencies are exactly refocused in phase at the same T_E time. If the π pulse is shifted by a time τ from the center of T_E, all frequency terms will rephase at $T_E + 2\tau$. During the time 2τ, the spins will dephase. If 2τ is short enough so that phase coherence will be retained, an adequate MR signal can be obtained. Let us consider the binary components, fat and water, whose resonant frequencies are ν_f and ν_w, respectively. The spins of each component revolve independently during a time interval of 2 τ and the phase difference at time T_E becomes 4 $\pi \tau \delta \nu$, where $\delta \nu$ is the frequency difference

between ν_f and ν_w. When the phase difference is π, the signal emitted from the volume element is the difference signal of fat and water components. This is the out-of-phase signal, I_{op}.

The resonance frequency difference of aliphatic and water protons is known to be 3.3 ppm, which is 300 Hz at 2 Tesla. The in-phase signal intensity, I_{op}, in a given voxel is the sum of signals from aliphatic and water proton,

$$I_{ip} = f I_f + (1-f) I_w \qquad (7)$$

and the out-of phase signal is the difference signal,

$$I_{op} = f I_f + (1-f) I_w \qquad (8)$$

where

$$I_f = e^{-\frac{T_R}{T_{1f}}}\left(1- 2\, e^{-\frac{T_E-\frac{T_E}{2}}{T_{1f}}} + e^{-\frac{T_E}{T_{1f}}}\right) \qquad (9)$$

and

$$I_w = e^{-\frac{T_R}{T_{1w}}}\left(1- 2\, e^{-\frac{T_E-\frac{T_E}{2}}{T_{1w}}} + e^{-\frac{T_E}{T_{1w}}}\right) \qquad (10)$$

where T_{1f}, T_{2f} and T_{1w}, T_{2w}, respectively, represent the longitudinal and spin-spin relaxation times of fat and water, and f is the fractional density of fat in each voxel. T_R is the repetition interval and T_E is the echo delay time in the spin echo sequence.

An important feature of Dixon's method is that a fat image and a water image(Fig.1) can be produced by subtraction and addition of the in-phase image and out-of-phase image, respectively. Fractional fat content can be quantitated from conventional (in-phase) and phase-contrast (out-of-phase) images by knowing the water proton and lipid proton resonant frequencies along with their relaxation times T_1 and T_2. To determine uniquely the fractional content, one needs to use phase sensitive reconstruction and then subtract or add the two images. Since the phase reconstructed image suffers seriously from magnetic field inhomogenei-ties, both static and dynamic (induced eddy current by time varying gradient fields), an additional field map is needed to correct for these effects. However, the phase difference, due to local magnetic field inhomogeneity, exceeding 2π leads to errors in the correction algorithm. The magnitude reconstruction method may lead to a non-uniqueness in determining a fat content without a priori knowledge of the dominant component in each volume element. If the system is not a binary, i.e. multicomponent system, or if an incorrect time delay, τ, is used in data acquisition, then the Dixon method fails to provide quantitative indices of fat/water content and may lead to incorrect interpretations.

Selective Method of the Chemical Shift Imaging:

The selective chemical shift method is basically a spectroscopy technique. From a classical viewpoint, the magnetization is tipped by 90 degrees into x-y plane and from a statistical viewpoint the population of spin up and spin down states is equalized. In order to equilibrate the spin population, an r.f. saturation pulse is normally used before a spin echo sequence. Since a long duration of saturating pulse has a narrow frequency spectrum, a highly homogeneous static field is required. The static field homogeneity should typically be less than 1.5 ppm within the volume to be imaged since the fat/water chemical shift separation is about 3.4 ppm.

A NMR chemical shift selective (CHESS) imaging was first presented by Haase et. al.[3] The pulse sequence consisted of a long saturation pulse followed by a dephasing gradient, and then a slice selective 90 degree and broadband 180 degree pulse. The length of the saturation pulse is determined by the separation of the resonant frequencies of each chemical component in the desired volume with consideration of the r.f. pulse shape and the spectral width of each component. To obtain a selectivity more than 95%, the saturation pulse width needs to be longer than $4/\delta$, where the δ is frequency separation. Since only one component is saturated, all other components contribute to the image.

Since the resonant frequencies of the saturating chemical components and imaging components are different, various frequencies should ideally be used for saturation and imaging. However, little difference is obtained in the resultant images if the imaging sequence (slice selective 90 and non-selective 180) are

relatively insensitive to the r.f. frequency. This is because the off-resonance effects for 3.4 ppm chemical shift is not significant in imaging.

Selective Echo Chemical Shift Imaging (SECSI) was proposed by Joseph.[4] The chemical component selection is made by use of a selective refocusing pulse. SECSI method was shown to be superior in selectivity to a CHESS method alone and a combined method (CHESS + SECSI) was even better. In such a combined method, the saturation sequence and the selective refocusing sequence are both frequency sensitive. Therefore, a combined method must use different frequencies for each sequence, although has not been addressed this r.f. frequency requirement.

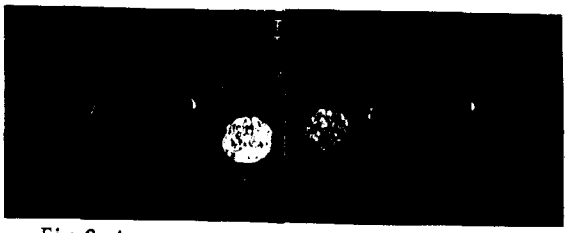

Fig.2 A water weighted(left) and a fat(right) weighted images of CHESS technique.

3. Discussion

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

CHESS imaging(Fig.2) does yield a lower signal to noise ratio compared to SECSI technique's(Fig.3). With increased field homoge-neity obtained by a shimming coil, the inhomogeneity in the vial is removed. Note Dixon's method is less susceptible to field homogeneities than the selective methods.

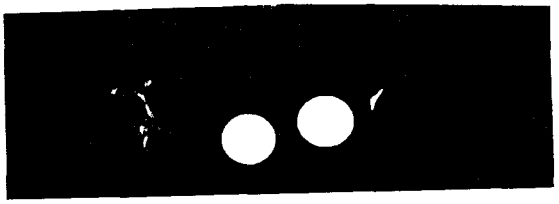

Fig.3 A water weighted(left) and a fat(right) weighted images of SECSI technique.

In figure 3, the SECSI technique was used to image a mouse. Good delineation between water and fat was obtained and the addition of these two images produces a normal spin echo image. Different refocusing pulse widths revealed different levels of selectivity for fat or water.

While the SECSI method images represent an only selected spectral component, frequency components other than fat and water would not be canceled in Dixon's method. The fat suppression ratios for the Mayonnaise vial of DM, CHESS and SECSI were 30, 140, and 240, respectively.

References:

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