ノート

Double-Quantum Filter Imaging of Sodium-23

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The method of double-quantum filter ^{23}Na NMR spectroscopy has been applied to ^{23}Na imaging. We have discriminated between ^{23}Na in the extreme narrowing condition (Na^+ in glycerol solution) and ^{23}Na in the slow motion condition (Na^+ in an albumin solution). The results suggest the possibility of correlation-time mapping of ^{23}Na.

1. Introduction

The method of double-quantum filter ^{23}Na NMR spectroscopy is selective for the double-quantum coherences from the $|1/2\rangle\langle -3/2|$, $|3/2\rangle\langle -1/2|$ rank 3 coherences. When $\omega\tau_c$ is around or larger than 1 (the slow motion condition, where ω is the Larmor frequency and τ_c is the correlation time of ^{23}Na), double-quantum coherence is evoked by using a double-quantum filter, When $\omega\tau_c$ is much less than 1 (the extreme narrowing condition), double quantum coherence cannot be evoked[1-5]. The double-quantum filter has been applied in erythrocytes[6], salivary gland[7] and heart[8], and the double-quantum coherences from the intracellular ^{23}Na and ^{39}K have beeen detected. In this study, we have applied this technique to ^{23}Na imaging, and have tried to discriminate between ^{23}Na in the extreme narrowing condition and ^{23}Na in the slow motion condition. The results raise the possibility of correlation-time mapping of ^{23}Na.

2. Materials and Methods

Sodium experiments were performed on a phantom consisting of two solutions : 1) an albumin solution (0.8 g albumin (Sigma A2153) and 1 ml 1 M NaCl solution) and 2) a glycerol solution (1 g glycerol and 1 ml 2 M NaCl solution). Each solution was placed in a methacrylate cuvette (1× 1 cm square in cross section with a height of 1.5 or 1.2 cm). A Biospec 150/4.7 spectrometer (Oxford Research Systems, 4.7 T) was used with a home-built ^{23}Na probe with a 20 mm internal

Key words double-quantum filter, sodium, magnetic resonance imaging

diameter, 4-turn solenoidal transmitter/receiver coil of 2.0 mm copper wire. Two variable capacitors (Voltronics, 38pF) were used for tuning (53.0 MHz) and matching (50Ω).

3. Results and Discussion

Since $\omega\tau_c$ of ^{23}Na in the albumin solution is larger than 1 (the slow motion condition) at 25°C, ^{23}Na in the albumin solution showed a signal from the double-quantum coherence. The spin-echo double-quantum filter, d-90°-τ/2-180°-τ/2-90°-δ-90°-acquire was applied with a 32-step phase cycle[2,9]. The transverse relaxation rate constants ($1/T_2$) of the $|-1/2\rangle\langle-3/2|$, $|3/2\rangle\langle1/2|$ coherences ($s_1=410$ sec^{-1}) and the $|1/2\rangle\langle-1/2|$ coherence ($s_2=100$ sec^{-1}) were obtained for ^{23}Na in the albumin solution with the creation time (τ) varied over the range from 0.25 to 20 msec ($r^2=0.997$, $n=41$). The double quantum evolution time (δ) was 0.005 msec, and the relaxation delay (d) was 0.5 sec. The spectral width was 10 kHz, the receiver dead time after the last 90° pulse was 65 μsec, and 1024 data points were used. Apparent values of $\omega\tau_c$ and τ_c were calculated to be 1.8 and 5.5×10^{-8} sec, respectively. The maximum intensity of the signal was obtained at the creation time of 4-5 msec.

Since ^{23}Na in the glycerol solution is in the condition of extreme narrowing ($\omega\tau_c << 1$) at 25°C, ^{23}Na in the glycerol solution showed no significant signal from the double-quantum coherence and showed an artifact of dispersion-like line shape with ca. 0.2% of the intensity obtained by the one-pulse sequence (d-90°-acquire). A single transverse relaxation rate constant (237±5 sec^{-1}) obtained for ^{23}Na in the glycerol solution by the conventional spin-echo sequence with the

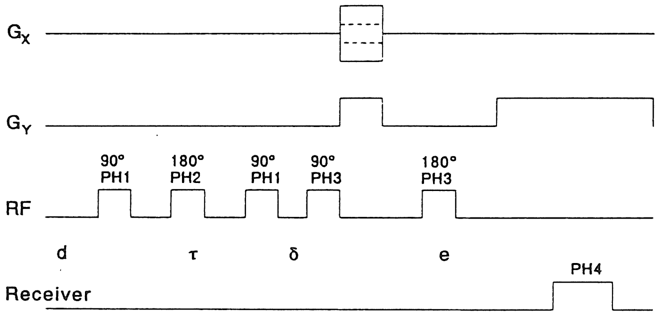

Fig. 1. Pulse sequence for double-quantum filter sodium imaging in the XY-plane without Z-direction slicing. Non-selective 90° and 180° pulses were 43 μsec and 86 μsec, respectively. The creation time (τ) was 4 msec, the evolution time (δ) 5 μsec, the echo time (e) 13.4 msec, and the relaxation delay 0.2 sec. The phase cycle for the double-quantum filter was as follows: PH1=(0°, 180°, 90°, 270°, 90°, 270°, 180°, 0°)$_4$, PH2=(0°, 180°, 90°, 270°, 90°, 270°, 180*, 0°)$_2$ (180°, 0°, 270°, 90°, 270°, 90°, 0°, 180°)$_2$, PH3=(0°)$_4$(90°)$_4$(180°)$_4$(270°)$_4$, PH4=(0°)$_2$(180°)$_2$(90°)$_2$(270°)$_2$(180°)$_2$(0°)$_2$(270°)$_2$(90°)$_2$.

受付年月日　1989年12月27日
別刷請求先　(〒444)　岡崎市明大寺町字西郷中38　岡崎国立共同研究機構整理研究所分子生理研究部　瀬尾芳輝

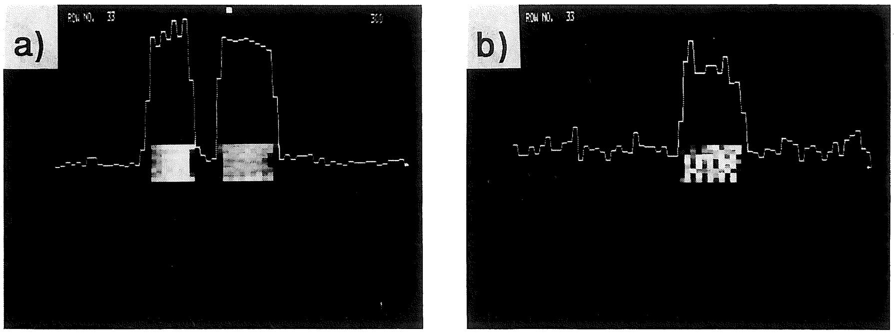

Fig. 2. (a) A conventional spin-echo ^{23}Na image in the XY-plane with an echo time of 13.4 msec, a relaxation delay of 0.5 sec and 64 accumulations. A line profile from the phantom containing an albumin solution (right side) and a glycerol solution (left side) is also shown. (b) A double-quantum filter ^{23}Na image in the XY-plane with a creation time of 4 msec, an evolution time of 5 μsec, an echo time of 13.4 msec and 256 accumulations. The level of suppression of the ^{23}Na in the glycerol solution is evident in the line profile.

echo time varied over the range from 0.01 to 5 msec (regression coefficient ±standard error, $r^2=0.991$, n=21).

^{23}Na images in the XY-plane were obtained with a field of view of 7×7 cm (1.5 gauss/cm) across a 64×64 matrix. The radiofrequency and gradient pulse sequences used for double-quantum filter sodium imaging are shown in Fig. 1. To avoid contamination of the signal from ^{23}Na in the extreme narrowing condition, the 180° pulse width was measured carefully with an accuracy of 0.2 μsec in every experiment.

Figure 2a shows a conventional spin-echo image obtained with an echo time of 13.4 msec. A line profile from the phantom is also shown. ^{23}Na is visible in both the albumin solution and the qlycerol solution. When we applied the double-quantum filter to the phantom with a creation time of 4 msec, the image from ^{23}Na in the glycerol solution was suppressed completely and only the signal from ^{23}Na in the albumin solution was observed in the image (Fig. 2b). One of disadvantage of the double-quantum filter might be low signal-to-noise ratio (1/5-1/10) compared with the conventional spin-echo sequence.

This result indicates the possibility of mapping the correlation time of ^{23}Na in biological systems. In the perfused rat mandibular gland, ^{23}Na in the intracellular and interstitial spaces have different relaxation rates. Since the detectable magnetization under the on-resonance condition is in proportion to $(e^{-s_2\tau}-e^{-s_1\tau})\cdot e^{-s_{dq}\delta}$, we may be able to selectively image ^{23}Na that has a specific correlation time.

4. Acknowledgements

This study was supported by the Collaborative Research Project Support (The British Council) and the Cooperative Program of the Laboratory for Magnetic Resonance Imaging and Spectroscopy (National Institute for Physiological Sciences). We thank O. Ichikawa, K. Suzuki, and H. Ohkawara for their technical assistance and Dr.K. Nagayama for helpful discussion.

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