IMPROVED CHARACTERIZATION OF HEALTHY AND MALIGNANT TISSUE BY NMR LINE-SHAPE RELAXATION CORRELATIONS

H. PEEMOELLER, R.K. SHENOY, AND M.M. PINTAR
Department of Physics, University of Waterloo, Waterloo, Ontario

D.W. KYDON
Department of Physics, University of Winnipeg, Winnipeg, Manitoba

W.R. INCH
Experimental Oncology Group, The Ontario Cancer Treatment and Research Foundation, London Clinic, London, Ontario, Canada

ABSTRACT We performed a relaxation-line-shape correlation NMR experiment on muscle, liver, kidney, and spleen tissues of healthy mice and of mouse tumor tissue. In each tissue studied, five spin groups were resolved and characterized by their relaxation parameters. We report a previously uncharacterized semi-solid spin group and discuss briefly the value of this method for the identification of malignant tissues.

INTRODUCTION

During the past two decades nuclear magnetic resonance (NMR) has been used extensively for the investigation of the properties of biological systems on a molecular level (1–24). Many studies (25–37) of relaxation times in healthy and malignant tissues were prompted by the observation (25) that the spin-lattice relaxation time (T_1) and spin-spin relaxation time (T_2) in a tumor generally were longer than in a healthy tissue. In these studies, the NMR relaxation measurements have been taken at only one time window on the free induction decay (FID). The resolution of the heterogenous spin distribution was improved if the relaxation measurements were taken at two time windows (23, 24). A further improvement of the resolution of spin distributions in these complex systems was achieved by a two-dimensional (2D) NMR technique (38, 39). This new approach is also called line-shape relaxation correlation NMR, or 2D-correlation NMR.

In the 2D-correlation spectroscopy the time evolution of the transverse decay, along the t-axis, and of the longitudinal recovery, along the τ-axis (38) are recorded and correlated. Typically 20 values of t and about 25 values of τ are used as compared with 1 value of t and about 25 values of τ in a standard NMR relaxation measurement. At each FID window, t, the magnetization recovery function, $M_x(t) - M_x(t,\tau)$, is plotted as a function of τ and graphically decomposed into components. The $\tau = 0$ intercepts and T_1 values of the components at each t are obtained. A plot of the $\tau = 0$ intercepts vs. t yields the main part of the FID of each magnetization component. Finally these FIDs are fitted to a Gaussian or an exponential. Projections to $t = 0$ of the FID, which are the equilibrium magnetizations, are obtained. If T_1 of magnetization components differ by more than a factor of ~5, the characterization of the spin groups is unambiguous. If the T_1 difference is smaller, additional corroboration, such as the $T_{1\rho}$–line-shape correlation, is needed.

In this report, we present the results of the standard FID and T_2 experiments as well as of the 2D-correlation NMR experiments in the mouse muscle, liver, kidney, spleen, and tumor tissues. With the 2D correlation approach, we also resolve a previously uncharacterized semi-solid spin group. In addition, proper measurements of the nuclear spin-relaxation times yield an increased malignancy index without increasing the time of the measurement.

EXPERIMENTAL METHODS

Normal tissue samples were removed from 8–10-wk old BALB/c mice. The tumor studied was the EMT6 fibrosarcoma (obtained from R.F. Kallman, Stanford, CA) grown in the dorsal subcutaneous tissue of BALB/c mice. The tissue samples were blotted free of blood and cut into ~0.1-cm^3 pieces. These were placed in ~25-mm glass tubes with 5-mm diameter and flame sealed.

NMR measurements were performed at 10°C with a Bruker SXP pulse spectrometer (Bruker Instruments, Inc., Billerica, MA) at 38 MHz. Since the receiver dead time was ~8 μs, the FIDs were recorded starting 10 μs

Dr. Peemoeller's present address is the Physics Department, University of New Brunswick, Fredericton, New Brunswick, E3B 5A3, Canada. Dr. Shenoy's present address is the Department of Physics, University of Maine at Orono, ME 04469.

after the 90° pulse. The T_2 was measured using the Carr-Purcell-Gill-Meiboom (CPMG) pulse sequence with 100-μs spacing between the successive 180° pulses. The T_1 was measured with the inversion recovery sequence 180°-τ-90° using ~25 values of τ.

The signal averaging and the data analysis were done with a Hewlett-Packard model 9845. A desk-top computer (Hewlett-Packard Co., Palo Alto, CA), interfaced with the spectrometer via a Biomation 805 transient waveform recorder (Biomation, Cupertino, CA). 10 and 100 FIDs were typically averaged in the T_1 and T_2 experiments, respectively.

RESULTS

The results of the proton FID experiment combined with a proton spin-echo envelope experiment on the five tissues are summarized in Table I. In each tissue the decay curve was graphically decomposed into five components, (Table I). These components are labeled solid (S), semi-solid (SS), semi-liquid (SL) and liquid (L_2 and L_1) according to their T_2 of ~20 μs, ~300 μs, ~5 ms, ~50 ms, and ~200 ms, respectively. Each S-component was fitted to a Gaussian curve. The T_2 of the Gaussian was taken to be the time in which the magnetization decays to one-half of its initial value.

All values shown represent the average of measurements on five different samples of a particular type of tissue. The accuracy of a typical measurement is ± 3%. However, because of biological sample differences, the standard deviations shown are much larger.

The FID and T_2 results in muscle agree with the published data (12, 23, 24). The SS-component, which was deduced indirectly a few years ago from measurements in fully deuterated muscle (24), is resolved in the present experiment in the natural muscle.

All the recovery curves of the proton magnetization were graphically decomposed into two components. Fig. 1 shows the T_1 values obtained from such decomposition, at 20 time windows along the FID in muscle, plotted as a function of time, t. The long and the short T_1 (represented by circles and crosses, respectively) are independent of the window position. Each of the T_1 values, given in Table I as the 2D

TABLE I
SPIN RELAXATION RESULTS IN MOUSE MUSCLE, LIVER, KIDNEY, SPLEEN, AND TUMOR

Sample	Spin group character	FID and CPMG T_2		2D Time evolution T_1 (FID)		
		Magnetization fraction	T_2	T_1	Magnetization fraction	T_2
		(%)	(*ms*)	(*ms*)	(%)	(*ms*)
Muscle	L_1	6 ± 2	190 ± 50			
	L_2	80 ± 2	46 ± 4	610 ± 60	85 ± 4	~1.5*
	SL	3 ± 1	6 ± 1			
	SS	4 ± 1	0.29 ± 0.11	90 ± 10	7 ± 3	0.42 ± 0.16
	S	7 ± 1	(18 ± 1) × 10^{-3}	610 ± 60	8 ± 3	(15 ± 4) × 10^{-3}
Liver	L_1	4 ± 1	190 ± 50			
	L_2	78 ± 2	39 ± 6	380 ± 30	89 ± 4	~1.5*
	SL	6 ± 2	6 ± 2			
	SS	5 ± 2	0.27 ± 0.11	80 ± 10	5 ± 1	0.22 ± 0.09
	S	7 ± 1	(16 ± 3) × 10^{-3}	380 ± 30	6 ± 3	(15 ± 4) × 10^{-3}
Kidney	L_1	5 ± 3	190 ± 30			
	L_2	79 ± 3	50 ± 8	490 ± 50	91 ± 1	~1.5*
	SL	5 ± 2	8 ± 1			
	SS	5 ± 1	0.36 ± 0.11	85 ± 10	5 ± 2	0.22 ± 0.10
	S	6 ± 1	(21 ± 1) × 10^{-3}	490 ± 50	4 ± 1	(17 ± 4) × 10^{-3}
Spleen	L_1	9 ± 4	210 ± 20			
	L_2	76 ± 4	60 ± 4	530 ± 20	90 ± 2	~1.5*
	SL	5 ± 1	6 ± 2			
	SS	5 ± 1	0.28 ± 0.03	85 ± 15	5 ± 1	0.17 ± 0.03
	S	5 ± 1	(19 ± 1) × 10^{-3}	530 ± 20	5 ± 2	(14 ± 3) × 10^{-3}
Tumor	L_1	15 ± 2	170 ± 50			
	L_2	75 ± 4	67 ± 15	760 ± 50	94 ± 1	~1.5*
	SL	3 ± 1	4 ± 1			
	SS	4 ± 1	0.30 ± 0.11	100 ± 10	3 ± 1	0.24 ± 0.07
	S	3 ± 1	(19 ± 6) × 10^{-3}	760 ± 50	3 ± 1	(16 ± 2) × 10^{-3}

All values shown represent the mean ± SD obtained from 10–100 measurements on five different samples of each kind.

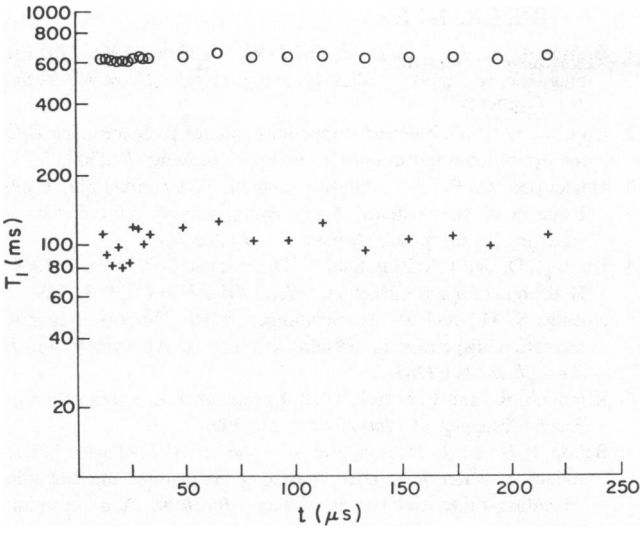

FIGURE 1 T_1 plotted as a function of window position in muscle tissue.

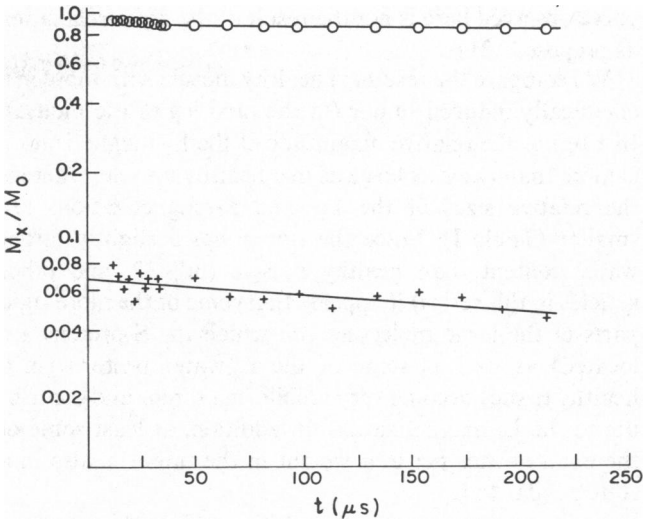

FIGURE 2 FID in muscle tissue obtained by the 2D NMR technique. The FID of the spin groups with long and short T_1 are represented by circles and crosses, respectively.

time evolution T_1 (FID), is the average of 100 values obtained from the analysis of the recovery curves at 20 windows in 5 different muscle samples. The T_1 values of the (L_1 + L_2 + SL + S) magnetization components (Table I) compare well with published results (27). The T_1 of the SS-magnetization component has not been detected accurately until now.

The τ = 0 intercepts obtained from the graphical decompositions are plotted as a function of t in Fig. 2. The FID of the magnetization component with long T_1 (represented by circles, Fig. 2) was decomposed graphically into two components (Table I). The main component was fitted to an exponential with a time constant T_2^* of ~1.5 ms. This spin-spin relaxation time is due to the field inhomogeneity broadening and is given in Table I as ~1.5* ms. The short component was fitted to a Gaussian (S-component with T_2 = [15 ± 4] μs in Table I). The FID of the magnetization component with short T_1 (represented by crosses in Fig. 2) is characterized by a single exponential with a T_2 of 400 μs (Table I). This component is labeled SS. The scatter in the data points in Figs. 1 and 2 could not be decreased significantly by an iteration procedure (39). The equilibrium magnetization fractions obtained from the projections to t = 0 of the two FID in Fig. 2, are shown in Table I in the column labeled 2D time evolution T_1 (FID).

The results of the same experiments and analysis in liver, kidney, spleen, and tumor tissues are summarized in Table I.

DISCUSSION

The relaxation times and the relative magnitudes of the associated magnetizations are very similar in all tissues studied (Table I). In each tissue, with the FID and T_2 experiment, five magnetization components are resolved. In the muscle tissue, a preliminary assignment of the magnetization components to molecular protons has been made. In the multiwindow study (23, 24) of natural and deuterated mouse muscle it was shown that in muscle the L_1- and L_2-protons are on the most mobile parts of large molecules and on molecules of the "free" water, respectively. The SL-protons are protons on water molecules with restricted mobility (bound water). The S-spins are on rigid parts of large molecules.

In the muscle tissue in which all water H and exchangeable large-molecule H were exchanged with deuterons (deuterated muscle) the SS-component was estimated (24) to have a magnitude of (3.4 ± 0.7)% relative to the total magnetization of the natural muscle. In the experiment reported here the SS-component in the natural muscle amounts to (4 ± 1)% and (7 ± 3)% of the total equilibrium magnetization of this tissue, as determined from FID-T_2 and 2D-time evolution T_1 (FID) experiments, respectively (Table I). Within the experimental error these three estimates of its relative magnitude do not differ. Although it is reasonable to assign the SS-component magnetization to protons on large molecules (24), it cannot be ruled out that a part of the SS-component (~1% of the total magnetization of the natural muscle) is due to bound-water protons.

It is interesting that in the muscle tissue the SS-proton group has T_1 = 90 ± 10 ms, whereas all the remaining protons have T_1 = 610 ± 60 ms (Table I). The implication of this large difference in T_1 is that the SS-protons are isolated from the other spins. In a recent study (21) of cross-relaxation effects in collagen and muscle it was shown that in the muscle the recovery curve for the magnetization of large molecules could be described by two apparent relaxation times of 17 and 625 ms. The fact that the shorter of these is about five times smaller than the T_1 of 90 ms resolved above (Table I) suggests that the apparent non-exponentiality in the magnetization recovery

curve observed here is not the result of the cross-relaxation as proposed (21).

We compare the results in healthy muscle with those in a chemically induced tumor (in the hind leg of the mouse). In a tumor the relative magnitude of the L_1-magnetization is more than twice as large as in a healthy muscle, whereas the relative sizes of the L_2- and S-magnetizations are smaller (Table I). Since the tumor has a slightly larger water content than healthy muscle (30, 32, and other articles in this series) it appears that some of the more rigid parts of the large molecules (on which the S-protons are located) as well as some of the L_2-water protons (in a healthy tissue) become very mobile in a tumor and contribute to the L_1-magnetization. In addition, at least some of the excess water per unit weight in the tumor is also in a state similar to L_1.

In a tumor, the mean value of $T_2 = (67 \pm 15)$ ms of the water (L_2) magnetization is ~50% larger than in a healthy muscle tissue (Table I) in agreement with the earlier observations (25, 26). The well-documented fact that the tumors have longer T_1 than healthy tissues is also evident in the present results; i.e., T_1 of a tumor is 760 vs. 610 ms for the muscle tissue (Table I).

For a magnetization component, i, a so-called malignancy index (35, and other articles in this series) is defined as

$$\Lambda(i) = \frac{(T_{1,i})_T}{(T_{1,i})_H} + \frac{(T_{2,i})_T}{(T_{2,i})_H}$$

where $(T_{1,i})_T$, $(T_{2,i})_T$, and $(T_{1,i})_H$, $(T_{2,i})_H$, are the relaxation times of the ith magnetization component in malignant and healthy tissue, respectively. For the muscle tumor $\Lambda(L_1) = 2.1 \pm 0.3$, $\Lambda(L_2) = 2.7 \pm 0.3$, $\Lambda(SL) = 1.9 \pm 0.3$, $\Lambda(SS) = 2.2 \pm 0.5$, and $\Lambda(S) = 2.3 \pm 0.4$. Only the $\Lambda(L_2)$ deviates significantly from $\Lambda = 2$ (for healthy tissue).

In earlier NMR studies of healthy and malignant tissues an average T_1 and T_2 of a number of components was used in obtaining a Λ-values. As a result, the Λ-value was nearer to 2. It is proposed that the resolution can be improved by using the $\Lambda(L_2)$ instead.

In summary, a semi-solid magnetization has been resolved and its relaxation times determined for each tissue. This magnetization is shown to be isolated from the other protons in the tissue. We also determined the so-called malignancy index for each of the five components into which the total tissue magnetization has been resolved. It was found that the index of the proton magnetization L_2, which is associated with the free-water protons is considerably larger than the index of the total magnetization (consisting of all the L-, SL-, SS-, and S-components combined).

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REFERENCES

1. Bratton, C. B., A. L. Hopkins, and J. W. Weinberg. 1965. Nuclear magnetic resonance studies of living muscle. *Science (Wash., D.C.)*. 147:738.
2. Cope, F. W. 1969. Nuclear magnetic resonance evidence using D_2O for structured water in muscle and brain. *Biophys. J.* 9:303.
3. Hazlewood, C. F., B. L. Nichols, and N. F. Chamberlain. 1969. Evidence for the existence of a minimum of two phases of ordered water in skeletal muscle. *Nature (Lond.)* 222:747.
4. Kuntz, I. D., Jr., T. S. Brassfield, G. D. Law, and G. V. Purcell. 1969. Hydration of macromolecules. *Science (Wash. D.C.)*. 163:1329.
5. Koenig, S. H., and W. E. Schillinger. 1969. Nuclear magnetic relaxation dispersion in protein solutions. I. Apotransferrin. *J. Biol. Chem.* 244:3283.
6. Kimmich, R., and F. Noack. 1970. Kernmagnetische Relaxation in Protein-lösungen. *Z. Naturforsch.* 25a:299.
7. Belton, P. S., R. R. Jackson, and K. J. Packer. 1972. Pulsed NMR studies of water in striated muscle. I. Transverse nuclear spin relaxation times and freezing effects. *Biochim. Biophys. Acta.* 286:16.
8. Held, G., F. Noack, V. Pollak, and B. Melton. 1973. Protonenspinrelaxation und Wasserbeweglichkeit in Muskelgewebe. *Z. Naturforsch. C. Biochem. Biophys. Biol. Virol.* 28:59.
9. Knispel, R. R., R. T. Thompson, and M. M. Pintar. 1974. Dispersion of proton spin-lattice relaxation in tissues. *J. Magn. Reson.* 14:44.
10. Civan, M. M., and M. Shporer. 1974. Pulsed NMR studies of ^{17}O from $H_2\ ^{17}O$ in frog striated muscles. *Biochim. Biophys. Acta.* 343:399.
11. Fung, B. M., and T. W. McGaughy. 1974. The state of water in muscle as studied by pulsed NMR. *Biochim. Biophys. Acta.* 343:663.
12. Hazlewood, C. F., D. C. Chang, B. L. Nichols, and D. E. Woessner. 1974. Nuclear magnetic resonance transverse relaxation times of water protons in skeletal muscle. *Biophys. J.* 14:583.
13. Finch, E. D., and L. D. Homer. 1974. Proton nuclear magnetic resonance relaxation measurements in frog muscle. *Biophys. J.* 14:907.
14. Kalk, A., and H. J. C. Berendsen. 1976. Proton magnetic relaxation and spin diffusion in proteins. *J. Magn. Reson.* 24:343.
15. Zipp, A., I. D. Kuntz, and I. L. James. 1976. An investigation of "bound" water in frozen erythrocytes by proton magnetic resonance spin-lattice, spin-spin, and rotating frame spin-lattice relaxation time measurements. *J. Magn. Reson.* 24:411.
16. Foster, K. R., H. A. Resing, and A. N. Garroway. 1976. Bounds on bound water: transverse NMR relaxation in barnacle muscle. *Science (Wash., D.C.)*. 149:324.
17. Packer, K. J. 1977. The dynamics of water in heterogeneous systems. *Phil. Trans. R. Soc. Lond.* B278:59.
18. Fung, B. M. 1977. Proton and deuteron relaxation of muscle water over wide ranges of resonance frequencies. *Biophys. J.* 18:235.
19. Civan, M. M., A. M. Achlama, and M. Shporer. 1978. The relationship between the transverse and longitudinal nuclear magnetic resonance relaxation rates of muscle water. *Biophys. J.* 21:127.
20. Eisenstadt, M., and M. E. Fabry. 1978. NMR relaxation of the hemoglobin-water protein spin system in red blood cells. *J. Magn. Reson.* 29:591.
21. Edzes, H. T., and E. T. Samulski. 1978. The measurement of cross-relaxation effects in the proton NMR spin-lattice relaxation of water in biological systems: hydrated collagen and muscle. *J. Magn. Reson.* 31:207.
22. Koenig, S. H., R. G. Bryant, K. Hallenga, and G. S. Jacob. 1978. Magnetic cross-relaxation among protons in protein solutions. *Biochemistry.* 17:4348.
23. Peemoeller, H., and M. M. Pintar. 1979. Nuclear magnetic resonance multi-window analysis of proton local fields and magnetization distribution in natural and deuterated mouse muscle. *Biophys. J.* 28:339.

24. Peemoeller, H., M. M. Pintar, and D. W. Kydon. 1980. Nuclear magnetic resonance analysis of water in natural and deuterated mouse muscle above and below freezing. *Biophys. J.* 29:427.
25. Damadian, R. 1971. Tumor detection by NMR. *Science (Wash., D.C.).* 171:1151.
26. Hazlewood, C. F., D. C. Chang, D. Medina, G. Cleveland, and B. L. Nichols. 1972. Distinction between the preneoplastic and neoplastic state of murine mammary glands. *Proc. Natl. Acad. Sci. U. S. A.* 69:1478.
27. Frey, H. E., R. R. Knispel, J. Kruuv, A. R. Sharp, R. T. Thompson, and M. M. Pintar. 1972. Proton spin-lattice relaxation studies of non-malignant tissues of tumorous mice. *J. Natl. Cancer Inst.* 49:903.
28. Hollis, D. P., L. A. Saryan, and H. P. Morris. 1972. A nuclear magnetic resonance study of water in two morris hepatomas. *Johns Hopkins Med. J.* 131:441.
29. Weisman, I. D., L. H. Bennett, L. R. Maxwell, M. W. Woods, and D. Burk. 1972. Recognition of cancer in vivo by nuclear magnetic resonance. *Science (Wash., D.C.).* 178:1288.
30. Inch, W. R., J. A. McCredie, R. R. Knispel, R. T. Thompson, and M. M. Pintar. 1974. Water content and proton spin relaxation time for neoplastic and non-neoplastic tissues from mice and humans. *J. Natl. Cancer. Inst.* 52:353.
31. Boveé, W., P. Huisman, and J. Smidt. 1974. Tumor detection and nuclear magnetic resonance. *J. Natl. Cancer Inst.* 52:595.
32. Saryan, L. A., D. P. Hollis, J. S. Economou, and J. C. Eggleston. 1974. Nuclear magnetic resonance studies of cancer. IV. Correlation of water content with tissue relaxation times. *J. Natl. Cancer Inst.* 52:599.
33. Fung, B. M. 1974. Non-freezable water and spin-lattice relaxation time in muscle containing a growing tumor. *Biochim. Biophys. Acta.* 362:209.
34. Kasturi, S. R., S. S. Ranade, and S. S. Shah. 1976. Tissue hydration of malignant and uninvolved human tissues and its relevance to proton spin-lattice relaxation mechanism. *Proc. Indian Acad. Sci. Sect. B.* 84B:60.
35. Koutcher, J. A., M. Goldsmith, and R. Damadian. 1978. NMR in cancer. X. A malignancy index to discriminate normal and cancerous tissue. *Cancer.* 41:174.
36. Peemoeller, H., L. J. Schreiner, M. M. Pintar, W. R. Inch, and J. A. McCredie. 1979. Proton T_1 study of coverage parameter changes in tissues from tumor-bearing mice. *Biophys. J.* 25:203.
37. Olszewski, K. J., J. Adamski, J. Bućko, N. Pislewski, and Z. Fischen. 1980. NMR study of the malignancy index and water content in a tumor uterus muscle. *Acta Physica Polonica.* A58:859.
38. Peemoeller, H., and M. M. Pintar. 1980. Two-dimensional time-evolution approach for resolving a composite free-induction decay. *J. Magn. Reson.* 41:358.
39. Peemoeller, H., R. K. Shenoy, and M. M. Pintar. 1981. Two-dimensional NMR time evolution correlation spectroscopy in wet lysozyme. *J. Magn. Reson.* 45:193.