NUCLEAR MAGNETIC RESONANCE IMAGING OF WOOD

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ABSTRACT

A newly developed NMR imaging method in radiology is used to obtain images of a piece of cherry firewood. The moisture contained in the firewood produces RF signals that are used to reconstruct a series of three-dimensional cross-sectional images. Detailed structural information such as annual rings, a worm hole, and an embedded knot are shown. An introduction to the practice of NMR imaging and some possible applications of this new technique in forestry and wood-science-related research are presented.

Keywords: NMR imaging, moisture content, wood structure.

INTRODUCTION

In the past decade, many new imaging procedures have been developed in medicine, which have dramatically improved the radiological diagnostic capability. Among these are X-ray computed tomography (CT), ultrasonography, digital radiography, and most recently, nuclear magnetic resonance (NMR) imaging. Before the advent of the CT, a three-dimensional (3-D) human body would appear as shadow images of many parts of the body overlaid on a two-dimensional X-ray film. With the unique tomographic capability, CT and NMR provide images of two-dimensional cross-sectional slices of the human body. These cross-sectional images eliminate the ambiguity of the shadow overlapping on the film. Realizing the 3-D-imaging capability of CT, scientists in other disciplines have been exploring the possibility of using CT to examine the structure of an object nondestructively. For example, the CT scan has been used in wood science to study the structure of logs (McMillin 1982), and in archaeology to obtain pictures of an embryo inside a fossilized dinosaur egg (J. R. Horner, personal communication). Because of its late arrival on the scene, NMR has yet to be explored extensively for possible applications outside the field of medicine.

In this paper, we report one such exploration—a piece of black cherry (*Prunus serotina* Ehrh.) firewood was imaged by a NMR scanner. The objective of this study is quite simple. We simply want to find whether it is possible to obtain images of wood with the NMR technique. Following a discussion of the physics for NMR imaging, the information obtained and some potential applications of this new technique in wood science research will be presented.

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PHYSICS FOR NMR IMAGING

Nuclei with an odd number of protons and/or neutrons tend to align their magnetic moments with an external magnetic field. If, for any reason, these atoms are disoriented from the direction of the magnetic field, they tend to precess about the direction of the magnetic field at a specific frequency known as the Larmor frequency, $\omega(x)$. The precessing frequency is proportional to the magnetic field strength $B(x)$, dependent upon the gyromagnetic ratio of the nucleus, γ and can be represented by the Larmor equation: $\omega(x) = \gamma B(x)$. Different nuclei have different gyromagnetic ratios so that in the same magnetic field they precess at different frequencies.

When a specific type of nuclei is exposed to a radio-frequency (RF) wave at their Larmor frequency, the nuclei will absorb the RF energy and realign their magnetic moments away from the magnetic field direction. This process is called resonance. The turning-away angle is proportional to the amplitude and duration of the RF wave. Once the excitation RF wave stops, the nuclei start losing energy to its environment with the magnetic moment moving back to its equilibrium direction, namely, the magnetic field direction while it is still undergoing precessing. This de-excitation process is called relaxation. Radio-frequency waves are generated to excite the nuclei by using an RF coil, which also functions as an antenna to receive the RF signals emitted from the nuclei during the relaxation process. The energy is released in the form of an RF wave, characterized by its Larmor frequency and discharged into the environment through two mechanisms: spin-spin and spin-lattice interactions. Each mechanism is characterized by a time constant called relaxation time. The spin-lattice type is called T1, while the spin-spin, T2. These relaxation times reflect the environment of the studied nucleus at a molecular level. With this information contained in the detected signal, the pathological and biochemical information of the sample can be revealed.

The spatial information contained in the NMR signal is obtained by superimposing a small magnetic field gradient on the main magnetic field (Pykett 1982; Mansfield and Morris 1982). With this technique, the magnetic field strengths will be slightly different at different locations. The same nucleus at unlike positions will have different Larmor frequencies. By analyzing the strengths of the received RF signal at different resonant frequencies, the spatial distribution of the imaged nucleus is obtained. Followed by a Fourier transformation of the signal (Kumar et al. 1975; Edelstein et al. 1980) and standard tomographic image processing technique similar to CT (Lauterbur 1973), a two-dimensional cross-sectional NMR image can thus be generated.

For more than 30 years, the NMR technique has been widely used to study the molecular structures of materials in solid-state physics and chemical compounds in chemistry. Damadian (1971) suggested that the relaxation times of NMR signals could be used to discriminate between benign and malignant tumors. This was the first indication of the NMR clinical application. The first NMR image of two thin-walled glass capillary tubes was obtained by Lauterbur (1973), using the above-mentioned spatial encoding method. Damadian (1977) and his colleagues published an NMR image of a living human. Theoretically, any kind of nucleus with an odd number of neutrons and/or protons can be imaged. However, hydrogen is the most often used nucleus in today's commercial NMR scanners

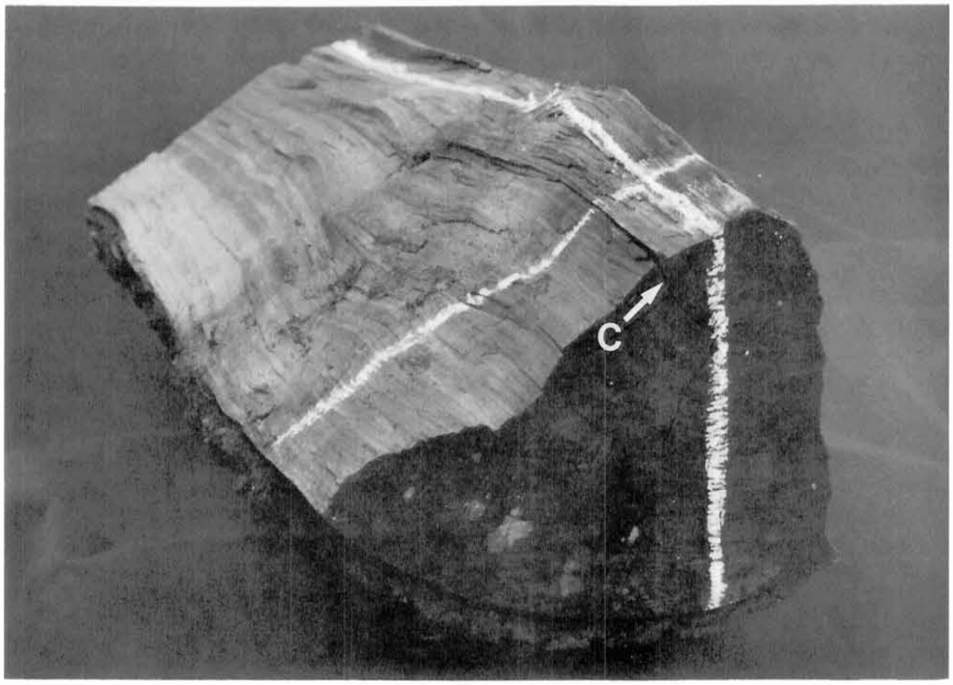

FIG. 1. A piece of black cherry firewood. It is fan-shaped, 40 cm long, and 14 cm in radius. The white line along the length of the firewood indicates the position where Fig. 2c was taken. The white line crosswise shows where the cross-sectional image, Fig. 3, was taken. The arrow indicates a ring check (C).

because of its sensitivity and abundance in the human body. Most of the scanners have a magnetic field strength between 0.15 to 2.0 tesla (one tesla equals 10^4 gauss).

EXPERIMENT AND RESULTS

The NMR unit used in this study is a 0.15 tesla resistive electromagnetic whole-body scanner, Teslcon (Technicare Corporation, Solon, Ohio). A piece of 40-cm-long seasoned black cherry firewood (Fig. 1) was first soaked in water at one end about one-third of its length for four weeks before the scan. The log was laid on the gantry of the magnet with its long side parallel with the main magnetic field. Both transverse and longitudinal images were obtained. The imaging technique used was a spin-echo technique (Mansfield and Morris 1982), in which 60 msec echo time and 50 msec repetition time were used. The imaging technique emphasized the contribution of proton density and T1 relaxation time of the log. For a single slice image technique, 4.5 minutes were required for data collection and 5 sec for image reconstruction. With the multislice imaging, depending on the technique and resolution, roughly 15 minutes are required to generate data for 32 slices of image simultaneously and 2 minutes to reconstruct them. Each image was 1.5 cm in thickness, and the spatial resolution was 1.2 mm.

A sequence of four consecutive pictures of the longitudinal views of the firewood,

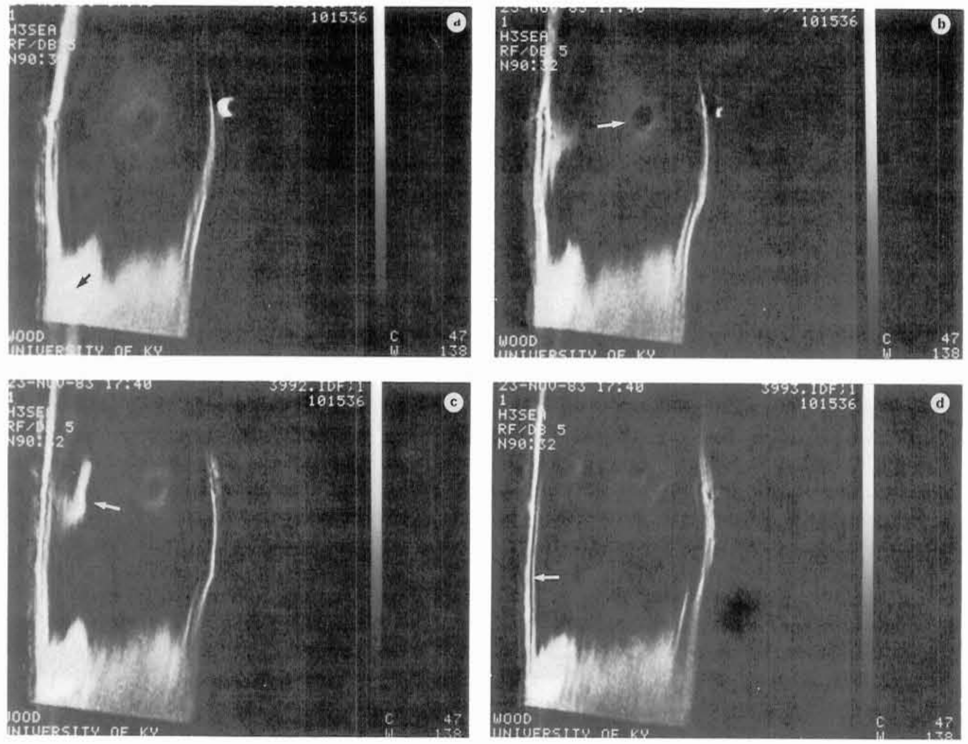

FIG. 2. Four consecutive longitudinal views of the firewood taken by the multislice technique. (a) The brightest spot at the lower left corner represents a part of sapwood soaked in water. (b) A dark shadow surrounded by a faded ring indicates an embedded knot. (c) A bright strip close to the upper left corner shows a worm hole. (d) A dark line on the left indicates the separation of the bark from the heartwood.

taken by the multislice technique, is given in Fig. 2. The lower end soaked in water is always brighter because it contains more moisture than the upper portion. The very bright portion in the lower left is sapwood, which contains more water than the less brighter heartwood to the lower right. This reconfirms a well-known fact that sapwood is more absorptive than heartwood. In Fig. 2d, a dark line on the left indicates the separation of the bark from the wood, because air produces no signal. If one observes closely, especially on Fig. 2d, different shades of brightness are seen even within the sapwood or heartwood, which results from unequal quantities of moisture in the earlywood and latewood. This is also demonstrated in the cross-sectional image of Fig. 3.

The longitudinal views also showed some defects contained within the firewood. A bright strip close to the upper left corner of Fig. 2c indicates the presence of a worm hole. The water had entered the firewood through the worm hole and penetrated longitudinally about 2 cm above and below the hole. To the right of the bright strip of Fig. 2c is a dark shadow surrounded by faded rings, indicating the presence of a buried knot. Similarly, the cross-sectional image of Fig. 3 shows another worm hole and also a ring shake located near the top of wedge. This weakness in the wood eventually caused the development of a ring check as shown in Fig. 1.

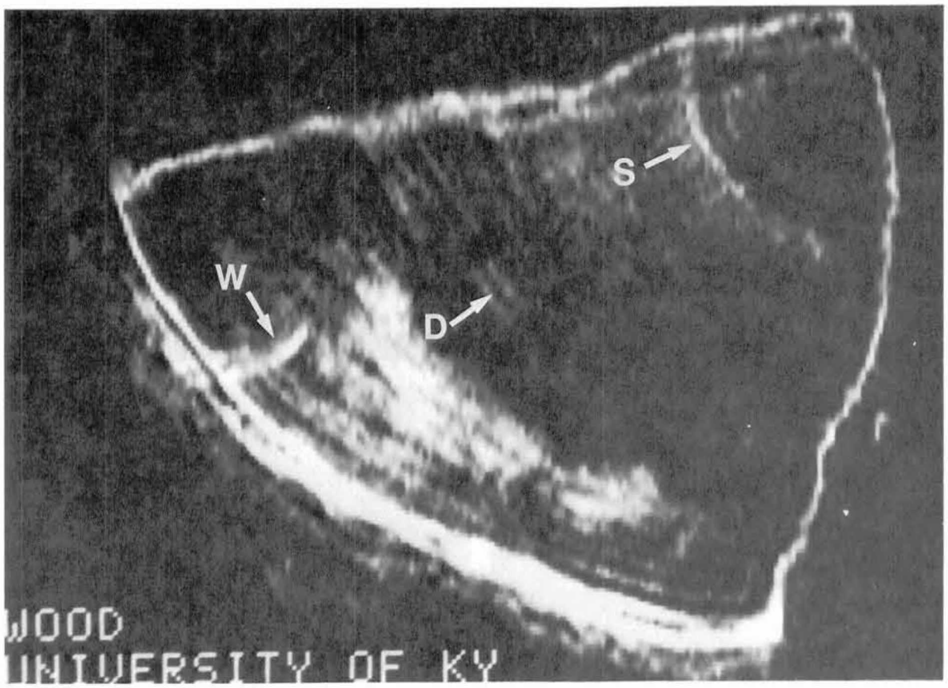

FIG. 3. A cross-sectional image of the log near the end soaked in the water. A worm hole (W), a ring shake (S), and the differences of the earlywood and latewood (D) are clearly shown.

DISCUSSION AND SUMMARY

Given sufficient moisture, many features of the black cherry wood such as sapwood-heartwood, earlywood-latewood, buried knot, and worm holes were identified on NMR images. Since the black cherry is a semi-ring porous species with gradual transition from earlywood to latewood, it is very encouraging that the difference between the former and the latter can be identified on the images generated.

Unlike the CT method, where the presence of moisture (particularly moisture content variations) represents a potential source of imaging error and causes difficulties in knot identification and location (Taylor et al. 1984), the NMR scanner relies on the moisture present in the wood to produce the images. The strength of NMR signal is directly proportional to the moisture content. Since moisture is usually present in the wood and the more moisture the better, the NMR imaging technique works. Even for samples with less moisture, a reasonable image can still be obtained by averaging a longer image time. This may very well be a major advantage of NMR scanner over the CT. Coupled with the low health risk of the NMR scanner, it is conceivable that the NMR scanner may be a viable alternative to the CT for schemes such as the automated lumber processing system (ALPS) suggested by McMillin et al. (1984). However, much work still lies ahead, not the least is in reducing the amount of time required to generate the images.

The authors are planning to conduct further studies to determine the amount of improvement in resolution and reduction of time required to obtain sharp images on an NMR scanner with a ten-times stronger magnetic field. Furthermore, at the current cost of approximately two million dollars, commercial application of the NMR scanner would not be very likely until the cost is substantially reduced. Yet, the potential for wood-science-related research is numerous. For example, notwithstanding past successes with NMR spectrometer in measuring wood moisture (Magnusson 1972; Nanassy 1973, 1974, 1976, 1978) and in measuring moisture movement (MacGregor et al. 1983; Peemoeller et al. 1985), the unique features of the NMR scanner provide new opportunities to nondestructively determine the amount of moisture, its spatial distribution, and its movement through wood with much larger and thus more realistic wood samples. Such information may then lead to possible improvements in the current practices of lumber drying and wood preservation.

In addition, the NMR technique is also known for its capability to generate biochemical information of a living system. The T1 and T2 relaxation times are used to categorize diseases in diagnostic radiology, they can very possibly be used as indicators in plant pathology studies. Nuclei other than hydrogen, such as fluorine, sodium and phosphorus, have also been used for imaging. By imaging these nuclei, many interesting detailed biochemical processes can now be obtained in vivo (Alger and Shulman 1984; Gadian 1982; Maudsley and Hilal 1984; Steiner and Radda 1984). For example, by monitoring adenosine diphosphate (ADP) and adenosine triphosphate (ATP) from a local NMR spectrum, the energy metabolic information can be obtained (Radda et al. 1984).

This new imaging technique has demonstrated its powerful spatial resolution and certainly will make a great impact on research in plant pathology, tree physiology and wood science.

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