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Detection of acoustic waves by NMR using a radiofrequency field gradient

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Abstract

A B_1 field gradient-based method previously described for the detection of mechanical vibrations has been applied to detect oscillatory motions in condensed matter originated from acoustic waves. A ladder-shaped coil generating a quasi-constant RF-field gradient was associated with a motion-encoding NMR sequence consisting in a repetitive binomial $1\bar{3}3\bar{1}$ RF pulse train (stroboscopic acquisition). The NMR response of a gel phantom subject to acoustic wave excitation in the 20–200 Hz range was investigated. Results showed a linear relationship between the NMR signal and the wave amplitude and a spectroscopic selectivity of the NMR sequence with respect to the input acoustic frequency. Spin displacements as short as a few tens of nanometers were able to be detected with this method.

Keywords: Radiofrequency field gradient; Acoustic waves

A present active area of research is the use of NMR to characterize elastic properties of living matter. Most of the methods are based upon a periodic application of static field (B_0) gradients for motion encoding [1–6]. An other open question is the possible role of low-frequency high energy acoustic waves in damaging biological tissues. Ultrasound waves have been previously detected with a standard MR elastography (MRE) imaging technique using static field gradients [7]. Despite the high quality of the published studies, transposing the classical MRE methods to the acoustic audiofrequency range would be somewhat severely complicated by an additional acoustic noise produced by B_0 gradient coil switching. A soundless NMR method based upon RF-field gradients has been successfully applied for the detection of oscillatory motions from a mechanical origin [8]. The purpose of the present work was an attempt to use this B_1-gradient method to measure the NMR response of a gel mimicking biological tissue excited by low frequency (20–200 Hz) acoustic waves.

The experimental setup, describing the sound wave generation, the wave guide, the positions of both the gel phantom and the ladder-shaped RF coil is depicted in Fig. 1. The acoustic intensities (or amplitudes) at the end of the wave guide were measured with a sonometer (CDA830, Chauvin-Arnoux, France) as a function of the input amplitude in the 20–200 Hz audiofrequency range. Those measurements were used to normalize the NMR magnitude signal to a constant acoustic intensity of 1 W/m^2 (120 dB sound level). Taking into consideration the air–gel interface, a transmission coefficient of 0.11% of the acoustic intensity was calculated. For a frequency of 40 Hz and a level of 120 dB in air, the level of the transmitted wave in the gel would be 90.4 dB, corresponding to 150 nm spin motion amplitude.

The NMR sequence used for the detection of spin motions was made of a repetition of a binomial $1\bar{3}3\bar{1}$ radiofrequency pulse, with definite pulse lengths and variable interpulse delays. In the absence of motion, such a binomial pulse cancels the observable transverse

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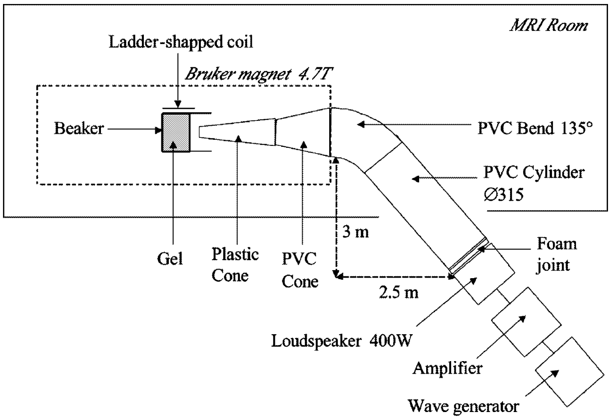

Fig. 1. Experimental setup. NMR measurements were performed using a Bruker Biospec 47/50 (Wissembourg, France) operating at 4.7 T. The home-built ladder-shaped RF coil [9] was positioned with its main axis (B_1 gradient axis) parallel to the static magnetic field. Coil length was 10 cm, corresponding to 7.5 cm RF gradient field. The sample was a glass cylinder (12 cm length, 10 cm diameter) containing a gel made of 2% agar (Sigma, St. Louis, MO), 150 mM NaCl in water, its open side facing the acoustic wave guide. The latter was made of a polyvinylchloride (PVC) cylinder (315 mm internal diameter) terminated by a conical focusing part with a final diameter of 65 mm facing the gel. The total length of the wave guide was 4.8 m and bent because of the RF-shielding room geometry. A 400 W loudspeaker (300 mm diameter) was positionned close to the PVC cylinder and was connected to a 200 W bass amplifier. Sinusoidal waves were generated by a phase-locked function generator (Thurlby Thandar Instruments, Huntingdon, UK). By systematically varying the wave amplitude and frequency from 20 to 200 Hz, the response of the loudspeaker and the wave guide was properly calibrated with acoustic power levels ranging from 90 to 130 dB.

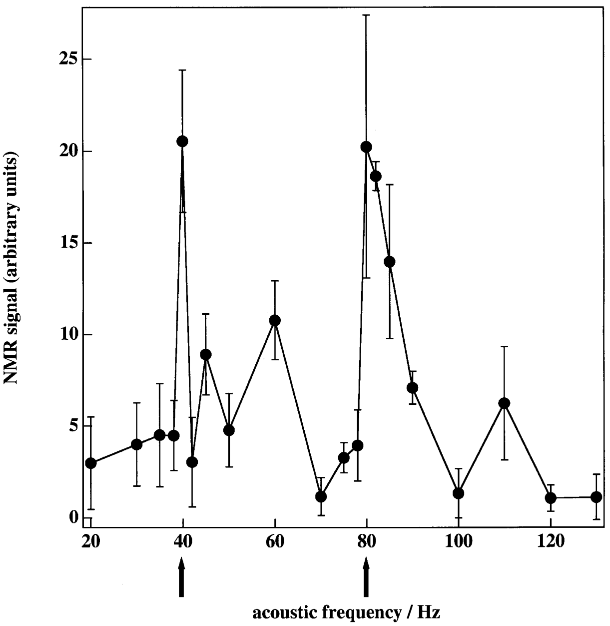

Fig. 2. Frequency selectivity of the NMR detection. A dedicated NMR pulse sequence [8] was used to monitor oscillatory motions within the gel phantom. A binomial $1\bar{3}3\bar{1}$ pulse sequence (1 ms pulse length, 5.25 ms interpulse delay) was repeated 16 times in order to encode a motion frequency of 40 Hz. The interpulse delay could be varied for detecting other required frequencies. The NMR pulse sequence was triggered by a transistor transistor logical (TTL) signal synthesized by the function generator. Any phase-shift between the sine wave function and the trigger signal was programable. The free induction decay (1024 data points, 2 kHz sweep width) was collected at the end of the train of binomial pulses. The total sequence time (relaxation delay, pulse train, FID) was an integer multiple of the acoustic period. In the absence of motion, the NMR water signal at the carrier spectrometer frequency (200.29 MHz) was cancelled. Serial acquisitions of FID were carried out for various acoustic frequencies which were incremented step by step. At least 5 FID were acquired for each conditions to assess the experimental reproducibility. The mean values of the NMR magnitude signal at the carrier frequency are given in the Figure. The error bars are the standard deviation. Arrows indicate expected frequencies for maximal NMR response.

magnetization at the carrier frequency. When a periodic displacement occurs, the flip angle distribution induced by an RF gradient across the object may not be exactly cancelled by a pulse of the same length and opposite phase, because of the spin motion during the interpulse delay. It has been shown that a homogenous flip angle distribution across the object could be obtained when the period and the phase of the cyclic motion matched those of the pulse sequence [8]. A better detection is expected when the length of the $1\bar{3}3\bar{1}$ binomial pulse is set at two times the acoustic period. Moreover, an increase in the nutation angle and hence the observable magnetization, as well as a better selectivity in frequency could be performed by repeating the RF excitation scheme prior to acquisition of the NMR signal [8].

The selectivity of the NMR pulse sequence (16 repetitions of the $1\bar{3}3\bar{1}$ binomial design) in detecting the corresponding acoustic wave frequency in the 20–200 Hz range was checked. A typical result where the NMR sequence was expected to encode 40 Hz waves is shown in Fig. 2. The peaks in NMR response for 40 Hz (nominal) and 80 Hz (first harmonic) acoustic frequencies were clearly detected. Such a behavior was previously identified in the case of mechanical waves using the same NMR pulse train [8]. Similar results with basic frequencies of 30 and 60 Hz were obtained (not shown). One must notice that the double-frequency mode should be detected with about twofold amplitude with respect to the fundamental mode [8]. This was never observed in our study, in agreement with the well-known inverse dependence of the acoustic wave amplitude as a function of its frequency. Note that due to the excessively small matter displacements, the signal-to-noise ratios of the experiments presented here were 4–5 times lower than those obtained in the previous study dealing with mechanical vibrations [8]. Nevertheless, spin displacements of several tens of nanometers were correctly detected. In control experiments, acoustic excitation of the gel phantom by the closed side of the glass container gave less than 1% of the NMR signal obtained by exciting on the open side (data not shown). This is in agreement with very small displacements due to the presence of both air–glass and a glass–gel interfaces which should greatly attenuate the acoustic amplitude. Moreover, since in those control experiments the waveguide was in contact with the glass reservoir, the absence of signal allowed to rule out the possibility of detecting mechanical vibrations with the present experimental setup.

Fig. 3 demonstrates the expected linear relationship between the normalized NMR signal and the square root of the acoustic intensity for various sound frequencies. In all cases, a stroboscopic acquisition was used, where the basic periodicity of the NMR pulse train was tuned to half of the acoustic frequency. The observed linearity could only be achieved if the flip angle α across the sample is small enough to allow to approximate $\sin(\alpha) = \alpha$. Taking into account the B_1-field gradient produced by the ladder-shaped coil ($\approx 100\,\mu\mathrm{T/m}$), acoustic amplitudes less than 1 μm, and total length of the pulse sequence less than 1 s, the flip angle should be below 0.01 rad, thus validating the approximation. Fig. 3 clearly shows that the slope of the NMR response abruptly decreased for acoustic frequencies higher than 80 Hz. Note that all experimental data were normalized to account for the variable response of the loudspeaker and the waveguide. The slope was expected to vary inversely with respect to the input frequency, a behavior not observed experimentally. Indeed, the plot of the slopes of the fitting lines in Fig. 3 versus the sound frequency could not be optimized by a simple reciprocal function of the frequency (data not shown). Such a discrepancy might be accounted for by the excessively large acoustic wavelength (ca. 10 m in gel phantom) with respect to the sample size (ca. 0.1 m). A more typical behavior might have been observed by using much higher acoustic frequencies.

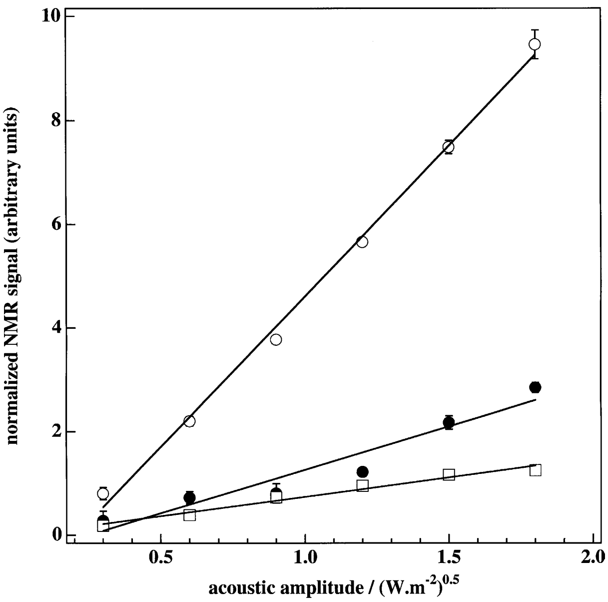

Fig. 3. Linearity of the NMR detection as a function of the acoustic wave amplitude. Serial acquisitions were achieved for a given acoustic frequency (open circles: 80 Hz; closed circles: 100 Hz; open squares: 120 Hz). The amplitude of the sound wave (square root of the acoustic intensity in the volume of air facing the gel, expressed in W/m^2) was incremented step by step and 5 FID were recorded for each amplitude. For an optimized detection, the length of the $1\bar{3}3\bar{1}$ binomial pulse was set at two times the acoustic period [8]. Each data point is the mean value of the five measurements. When displayed, the error bars are the standard deviations, otherwise they are included in the symbol size. The lines are the best linear fits of the data points.

To our knowledge this is the first report on the use of radiofrequency field gradients to detect condensed matter displacements originating from acoustic waves. This NMR method, although preliminary, allowed the visualization of motion amplitudes as low as a few tens of nanometers. Vibrational motions with amplitudes smaller than 100 nm were also detected using standard MRE [6]. MRI of focused ultrasonic fields with displacement amplitudes of several tens of nanometers was also performed using oscillatory gradients of static magnetic field [7]. However, the sound frequency used in the latter study (515 kHz) involved rather high acoustic power (about 10 W/cm^2 at the focus) in order to achieve measurable motion amplitudes. The advantage of using ultrasound rather than mechanical vibrations to characterize dynamically viscoelastic properties of tissues in patients lies in the easiness to install ultrasound probes in standard MR systems. On the contrary, the use of a rigid rod for mechanical excitation of an organ such as breast or muscle is far more tedious. From a biological point of view, the weak NMR signal obtained by acoustically exciting the closed side of the gel phantom suggests that the effect of strong low-frequency acoustic waves on organs protected by a bone-barrier (e.g., brain) should be harmless. On the contrary, attention must be paid when dealing with organs like liver or skeletal muscle.

A further development of the present work would then be to extend this RF field method to detection frequencies in the ultrasound range. This can be achieved with standard RF electronics present in modern NMR spectrometers, where short RF pulses (several μs) can be repeated with high duty cycles. The remaining point is that the presented method is spectroscopic. It would be more valuable if associated with space encoding. One interesting but arduous possibility would be the combination of motion detection with B_1 surface imaging [9], where only RF field gradients would be used for mapping acoustic waves, taking advantage of the low sensitivity to eddy currents and susceptibility artifacts.

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