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MAGNETIC RESONANCE IMAGING OF ELASTIC WAVE FIELDS IN CONDENSED MATER

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ABSTRACT

A new unsynchronized method of MRI operating with no prior knowledge of intensity, direction and frequency of mechanical waves is proposed. The experimental results obtained on test-objects fit well with theoretical calculations.

1 - INTRODUCTION

At the beginning of the nineties, we have developed a method of motion sensitizing gradient in-conjunction with a periodic mechanical compression for Magnetic Resonance Imaging [1-4] and Elasto-Magnetic Resonance Spectroscopy (EMRS) [5] of visco-elastic properties; the first method has been successfully applied, for the case of transversal elastic waves, in 1995 by Muthupillai et al. [6,7] under the name of Magnetic Resonance Elastography and by Plewes et al. [8,9] in the range of low frequencies for transverse waves [8], as well as for longitudinal waves at ultrasonic frequencies [9]. MRI can be a good challenger for such measurements as it provides imaging of mater at higher quality than usually obtained by other imaging methods. The goals of this study are: (i) to develop a faster method compatible with in-vivo clinical MRI, (ii) to obtain with such a method the movement analysis in any space direction, (iii) to make accessible a method of spectral analysis of periodical movement.

2 - THEORETICAL BASIS OF EMRS

The concept of elastic waves imaging [2], [4] has been based on the method of motion-sensitized MRI. The Larmor frequency is a linear function of the local magnetic field. Thus, in a heterogeneous field this frequency encodes the spatial spin distribution in the sample. If, in addition, the spins move in the presence of the magnetic field gradient, then the phase of the transverse magnetization component, originating from these spins, reflects the time evolution of the localization of spins [2-5], [10]. If the spins undergo periodic dislocations induced by an elastic wave with frequency ν_e, their position can be described by the equation of harmonic motion. In the EMRS method [5], sinusoidal magnetic field gradient with frequency ν_G was assumed. This means that the motion of spins forced by an elastic wave in the presence of the gradient $G(t)$ generates a phase distribution described by the following expression [5]:

$$\frac{\Delta\Phi}{F} = \frac{1}{2\pi\nu\left(\alpha-1\right)}\cos\left\{2\pi\nu\left(\alpha-1\right)\left(t+\frac{NT}{2}\right)+\varphi-Kr\right\}\cdot\left[\sin\left\{\pi\nu\left(\alpha-1\right)NT\right\}\right] \tag{1}$$

where: $F = \gamma G_0 \xi_0 \cos\Psi$ characterize the experimental conditions, $\alpha = \nu_e/\nu_G$, Ψ is the angle between the direction of displacement ξ and gradient G, G_0 and φ denote the amplitude and phase of the magnetic field gradient, respectively, ξ_0 denotes the amplitude of harmonic motion, N is the number of periods T of the changes in the magnetic field gradient, K is the wave vector.

The function described by Eq. (1) has a resonant and anisotropic character. This means an amplitude discrimination of frequencies satisfying the resonance condition $\nu_e = \nu_G$. Hence, it is possible to carry out: spatial, frequency-amplitude and directional analysis of complex elastic wave fields [5] originating from both external and internal sources. This means that it is possible to obtain spectral composition of this field at any point of complex systems and, as a result, to determine the properties of viscoelastic features of the matter of environment in which the waves propagate [6-10]. In order to measure the resonance between a mechanical vibration and the gradient oscillation, we propose to adapt the SPAMM sequence presented by Axel [11]. The conventional SPAMM sequence is used to follow the abnormal contraction of the cardiac wall in presence of an ischemic pathology. The sequence creates a grid on the image. The grid is created by the following preparation cluster added to a normal gradient echo sine-sequence: $90°_x$ — gradient G_x — $90°_y$. The first 90° pulse creates a magnetization in the transverse plane. The gradient pulse in one spatial direction (for example X) induces a phase modulation in this direction. This phase modulation will be responsible of the grid on the image. The second 90° pulse transfers the phase modulation in a longitudinal M_z direction. This modulation is red out with the imaging sequence applied after the preparation cluster. For our application, we have kept the same basic cluster with some modulations: (i) After the SPAMM preparation, we applied the sinusoidal gradient sensitive to the mechanical vibration. The intensity of this bipolar gradient pulse is fixed to a high value in order to create a sensible phase modulation. (ii) The second modification concerns the sequence. We propose to add the preparation pulse only one time at the beginning of the sequence. We do not repeat it before the acquisition of each Fourier line. We use for that a turbo FLASH sequence with a TR of 7 ms and a TE of 4 ms. The main interest of this sequence is the absence of averaging of the preparation pulse effect. The coupling between mechanical vibration and gradient commutation is only achieved during one short evolution period. The grid evolution at the end of the short period is then "frozen" on the image. This sequence can be used in a spectroscopic mode to detect and estimate the frequency of the mechanical vibration. One other advantage of the method is the capability of turning the grid orientation by changing the gradient orientation in the preparation cluster. It is then possible to put the grid orientation perpendicular to the motion direction in order to increase the sensibility.

3 - MATERIAL AND METHOD

Investigations were carried out by the use of NMR tomography systems: 0.2 T open SIEMENS MRI. Transverse elastic waves were generated in a gel phantom using a vibrational table set in motion by vibrations forced by means of a BRUEL-KJAER no. 4810 vibrator and transmitted by a 3 m long Plexiglas rod with preset transmission properties. Homogeneous gel phantom was placed in a rectangular cuvette with dimensions 12.5 ×12.5 ×20 cm. Figure 1 shows the schematic representation of the appliance employed (Fig. 1a) and the sequence of RF pulses and magnetic field gradients (Fig. 1b).

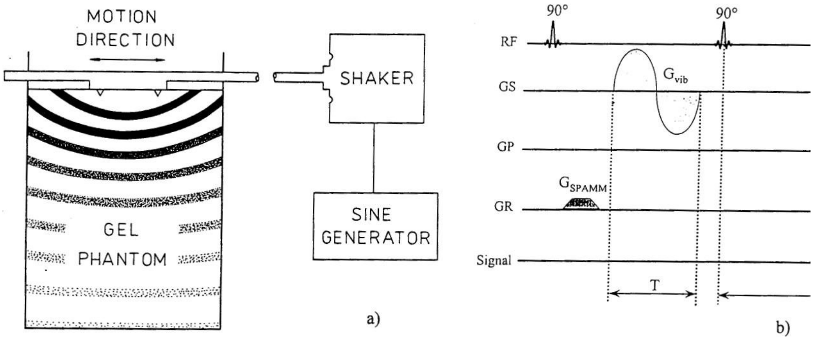

Figure 1: Schematic representation of the appliance (a) and pulse sequence diagram (b).

4 - RESULTS

Figure 2 shows the MR phase images of the gel in the presence of a sinusoidal magnetic field gradient with a frequency of 50 Hz without vibrations (Fig. 2a), with a 50 Hz vibration without sinusoidal magnetic field gradient (Fig. 2b), and in the presence of vibrations and sinusoidal magnetic field gradient (Fig. 2c) with the employment of one period of the gradient changes and with satisfied resonance condition $\nu_e = \nu_G$= 50 Hz. These images confirm the principal assumption of the method as to the possibility to create the MR phase images of elastic waves by the use of the proposed sequence of RF pulses and magnetic field gradient. Contrary to previous methods [6,7], the images were obtained in a time of the order of 4 s. In order to verify the extent in which the method satisfies the resonance condition $\nu_e = \nu_G$, imposed by Eq. (1), a series of images was created for a fixed frequency of the transverse elastic waves, $\nu_e = 50$ Hz, and varying frequency, ν_G of the magnetic field gradient changes.

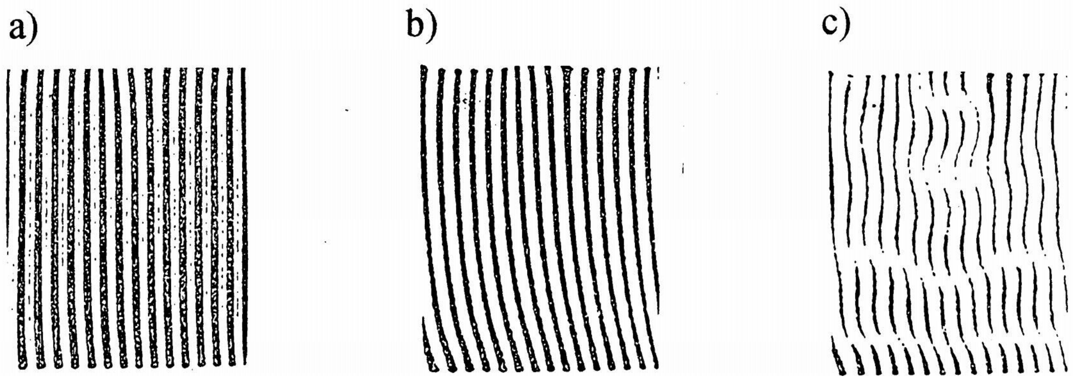

Figure 2: Phase images of gel: (a) in the presence $G(t)$ without vibrations, (b) with vibrations without $G(t)$ and (c) in presence of vibrations and $G(t)$.

Figure 3 shows images obtained for selected values of ν_G and one period of the changes in the magnetic field gradient, $N = 1$. As seen, the image is the clearest with the resonance condition being satisfied.

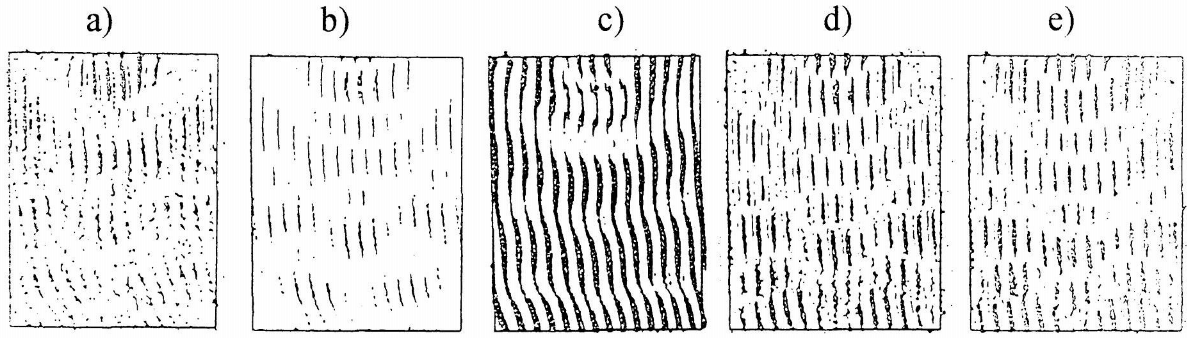

Figure 3: Images obtained for selected values of ν_G: 27.7 (a), 41.6 (b), 50 (c), 58.4 (d) and 72.7 (e) Hz.

Figure 4 shows the predicted run of the relative values of the function from Eq. (1) for three selected numbers of period, $N = 1$, 4 and 10. On the background of the theoretical dependence, the points represent the relative change in the total intensity of the black of images from Fig. 3 as a function of relative frequency α. The points are well fit to the theoretical curve obtained for $N = 1$ (in accordance with the experiment carried out). Theoretical curves for $N = 4$ and 10 show how the width of the discrimination band of the method is reduced when increasing *N*. The method was also verified as regard direction. Figure 5 shows two images recorded for two values of the angle Ψ between gradient G and the direction of displacement, ξ, forced by an elastic wave. The image of the elastic wave is clear and distinct for $\Psi = 0$ and disappears for $\Psi = 90°$.

5 - DISCUSSION AND CONCLUSION

The results presented above confirm the theoretical predictions suggesting the usefulness of the method for the analysis of the intensity, directions and frequencies of an unknown elastic wave field. A partial experimental verification was carried out for a previously worked out method of EMRS [5] in the range of NMR. This experiment made possible: (i) the verification of the principal assumptions of the EMRS, i.e. its resonance character and directional selectivity, (ii) the verification of the RF pulses and magnetic field gradient sequence enabling MR phase images of elastic waves with selected frequency to be obtained in a short time. One of the main advantages of the method is the resonance and anisotropic detection of a complex elastic wave field. This enables complete characterization of elastic wave field (intensity, direction and spectral analysis) opening to various possible applications of MRI such as: (a) investigations of the emission properties of internal vibrational sources of elastic waves, e.g. deformation emission of materials, emission from natural vibration sources such as functioning biological organs, emission from

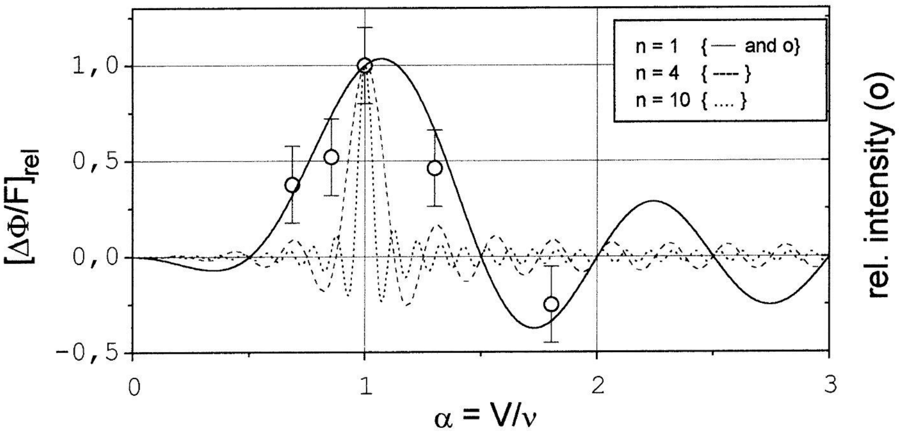

Figure 4: Predicted run of the relative values of function (1) for three selected numbers of period N = 1, 4 and 10.

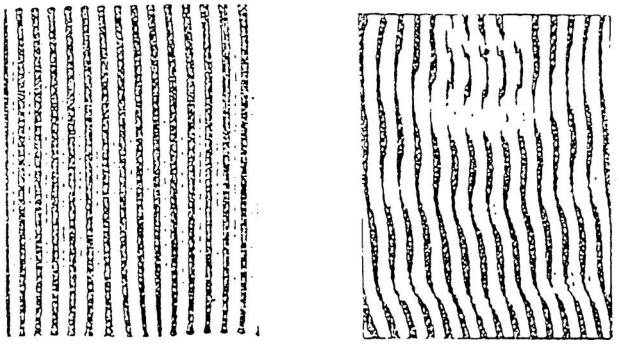

Figure 5: Images recorded for two values of the angle Ψ=0 and 90°.

technical sources, (b) investigations of elastic waves propagation conditions in complex systems, and (c) investigations of viscoelastic properties of materials, also in complex systems. Of particular interest seem biomedical applications of the method discussed, including in-vivo diagnostics such as examination of heart functions, pathological changes in elastic properties of tissues, as well as spatial and time structure of organs. One may assume that the EMRS will also turn out to be efficient as regards longitudinal waves in the range of high frequencies of elastic waves.

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