Fast Field-Cycling NMR Relaxometry Extended in the Ultra-Low Field Region: Calibration Method and Acquisition of T1-Dispersion Curves that reach 2.3 μT

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Synopsis

A graph of T_1 versus magnetic field obtained via Fast Field-Cycling (FFC) NMR relaxometry techniques can be developed into a new diagnostic tool thanks to the information about molecular dynamics that it provides. In this work, a novel method that compensates for the environmental fields acting on an FFC relaxometer is analysed, and applied to acquire measurements in the μT region for the study of much slower molecular motions, that was not previously possible. The results acquired from human cartilage indicate motions occurring in a slow time scale (0.1 to 10 ms), which show promise for clinical studies.

Purpose

Fast Field-Cycling (FFC) NMR relaxometry is a technique that measures the spin-lattice relaxation time T_1 over a range of magnetic fields, and provides curves that indicate the dispersion of T_1 values with the applied field. These are known as T_1-dispersion curves and are already used for the investigation of the dynamical and structural features on the molecular level of a range of complex systems. The dispersion curves are expected to provide clinically relevant information and develop into a new diagnostic tool, through the method of FFC-MRI[1].

The range of the dispersion curves acquired in most biological applications extends from 10 kHz to 10 MHz in terms of measured proton Larmor frequencies, probing molecular motions of submillisecond to microsecond time scales. The segment of the dispersion curve that extends below 10 kHz (the ultra-low field (ULF) region) provides information on even slower molecular dynamics of time scales in the range of tens of milliseconds, and can be clinically useful, leading to new types of contrast. However, for the application of ULF FFC techniques, compensation for the unwanted environmental magnetic fields is necessary since their magnitude becomes comparable to B_0 and leads to artefacts[2]. In this work, have implemented a novel calibration method based on the work of Anoardo et al.[2], applied on a commercial FFC NMR relaxometer to compensate for the environmental magnetic fields acting inside its bore. The aim is to obtain dispersion curves from biological samples that extend to the ULF region and to explore the potential that this segment has in medicine.

Methods

The calibration is achieved with the implementation of FFC measurements in a range of fields close to zero, along with correction fields of varying magnitude and orientation applied by the relaxometer. During this process, the magnetisation precesses around a resultant field of unknown magnitude and orientation composed of the correction and stray field, with the frequency of precession determined by its magnitude. As the correction fields vary, the direction and magnitude of the resultant field change, leading to variations in the frequency of precession. The novelty of our approach is the measurement of the precession frequency for each correction field applied, and the determination of correction fields that lead to the effective calibration by using the model:

$$\sqrt{\left(B_c^l + B_e^l\right)^2 + \left(\left(B_c^t \cdot sin(\theta)\right) + \left(B_e^t \cdot sin(\phi)\right)\right)^2 + \left(\left(B_c^t \cdot cos(\theta)\right) + \left(B_e^t \cdot cos(\phi)\right)\right)^2}$$

(where B_c^l and B_e^l the longitudinal correction and environmental fields, B_c^t and B_e^t the transverse correction and environmental fields, θ and ϕ the azimuth angles of B_c^t and B_e^t). This is applied to fit the graphs that plot the measured precession frequency for the range of the applied correction fields.

Results

The correction fields found by the curve fitting (Figure 1) are: B_c^l = 500 Hz, B_c^t= 66 Hz, and azimuth angle: -45°. These are validated according to known dispersion curves obtained from the polymers polydimethylsiloxane and polybutadiene.

Following calibration, dispersion curves that extend to the ULF region were acquired from two samples of cartilage taken from different regions of the femoral head of a patient suffering from osteoporosis (Figure 2). The models applied to fit the measured dispersion curves are a power law composed of three segments fitting the background and a model describing the quadrupolar relaxation in proteins[3] fitting the three quadrupolar peaks shown between 0.4 to 0.9 MHz, and 1.5 to 3.5 MHz. The curves extend to minimum applied B_0 of 100 Hz (2.3 μT) and 260 Hz (6.1 μT), while the segment of the ULF region shows a different slope from the one of the central (10^4 to 10^6 Hz) and the high field region (10^6 to 10^7 Hz). Additionally, a difference is observed in the offset between the two background curves acquired from each patient, while the three quadrupolar peaks are consistently shown in the same regions.

Discussion

The quadrupolar peaks are developed due to known interactions between ^{1}H and ^{14}N nuclei[3]. Additionally, the

calibration reveals a segment below 10^4 Hz that shows a different slope from the rest of the curve, indicating a different type of motion that occurs in a time scale of 0.1 to 10 ms.

Conclusion

In this work, we have shown that an FFC NMR relaxometer can be calibrated for experimentation in the ULF region. Based on the acquired results on cartilage, this has potential applications in medicine by providing information on extremely slow dynamic processes in tissues. Our work indicates that, the differences observed between the slopes, offset of the background, and quadrupolar peaks of the dispersion curves are likely to provide clinically relevant information and can form the basis of new types of contrast.

Acknowledgements

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References

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Figures

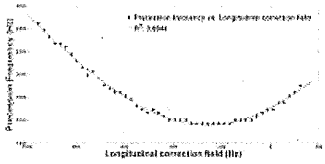

Figure 1. Graph of the precession frequency versus the longitudinal correction field.

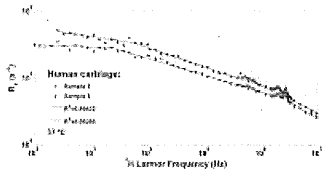

Figure 2. R_1-dispersion curves ($R_1=1/T_1$) obtained from two samples of human cartilage.