Observation of radiation damping effects in a birdcage resonator with hyperpolarized 3He at 1.5T

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Introduction and Background Theory Radiation damping is a non-linear effect caused by an interaction between the sample magnetization and the tuned RF resonator [1]. It can be described as the action of a 'counter' field produced by the current induced in the coil, which exerts a torque opposite to that of B_1^+ to 'push back' the sample magnetization towards the longitudinal direction. In a quantum description it is described as a spontaneous emission or maser effect [2]. In experiments with short T_2^* or imaging experiments where gradients cause rapid dispersion, radiation damping is less likely as the interaction between the transverse magnetization vector and the coil is rapidly quenched. In the original analysis [1], the radiation damped FID was given by $sech(t/\tau_{rd})$ where $\tau_{rd} = (2\pi\eta M_0 Q\gamma)^{-1}$ is the damping time constant, M_o is the longitudinal magnetization vector, Q is the quality factor, and η is the filling factor. Gueron et al [3] gave the damping time in SI units as $\tau_{rd} = (Q\pi\eta\gamma M_0\mu_0/2)^{-1}$, with M_o the longitudinal *magnetization density*. The effect has been described previously in low field hyperpolarized (HP) gas NMR [4], where T_2^*'s are very long, using small pick-up coils with high Q, and high η. Birdcage resonators have spatially homogeneous B_1 profile [5], important in HP gas MRI which is very sensitive to flip angle by virtue of the non-renewable polarization. The accurate definition and calculation of η for a birdcage resonator, and its relationship with Q is the subject of discussion [6,7], indeed it has been suggested that sensitivity to radiation damping may be a means of measuring η [6]. In this work we probe radiation damping effects with HP ^{3}He samples at 1.5T, using a volume optimised birdcage coil with high Q and good homogeneity.

Methods Measurements were conducted on a 1.5T whole body MRI system (Eclipse-Philips Medical System). The system was fitted with a transmit-receive circuit for ^{3}He at 48.5 MHz. The ^{3}He gas (Spectra Gases) was polarized on site by optical pumping with Rb spin exchange apparatus (GE). Studies were performed using two gas phantoms: **i)** 1 litre Tedlar plastic bags and **ii)** a 270 ml spherical glass cell. The ^{3}He polarization, *P*, was measured at 27% for the bag experiments and 38% for the cell experiments. The magnetization density of the samples was calculated from $M_0 = \mu PN/2$, where μ is the nuclear magnetic moment of ^{3}He and *N* is the number of ^{3}He atoms per unit volume. In the bag experiments, 80 ml ^{3}He was mixed with 920 ml N_2 at 1 atm giving $M_0 = 6.4\times10^{-3}$ JT^{-1}m^{-3} which is comparable to the M_0 of a 1-*l* sample of H_2O at 1.5T ($M_0 = 4.8\times10^{-3}$ JT^{-1}m^{-3}). In the cell experiments, 260 ml of ^{3}He at 1.2 atm pressure (P=38%) was used, giving M_0=0.13 JT^{-1}m^{-3}. The dissimilar sample volumes allow the investigation of η.

Fig. 1

RF coil: A quadrature T/R birdcage was purpose built –**Fig.1.** The low-pass birdcage had 15 cm inner diameter, 22 cm shield diameter and twelve 19 cm legs. Measured Q with the coil matched inside the magnet was 250 at 48.5 MHz. Isolation between the two orthogonal ports was -26dB. A 2-D B_1 mapping sequence using spoiled gradient echo imaging was used to characterise the coil homogeneity with a 1 *l* bag phantom (< 15% variation across bag). Calculation of η is an area of debate [6,7], however an upper limit is the ratio of the sample and coil volumes: $\eta < V_s/V_c$, this gives η<3.6% for the cell and η<13.8 % for the bag. We then estimated η from the ratio of RF magnetic energy of the sample and the total stored magnetic energy, giving η = 0.32 % for the bag and η = 0.085% for the cell.

Radiation damping was probed by acquiring *n*=115 sequential pulse-acquire data acquisitions –each one followed by spoiling of the transverse magnetization with a large crusher gradient (20 mTm^{-1} for 10 ms). The signal in the pre-amp was attenuated by 18 dB to avoid saturation or compression and possible clipping of the large transverse signal. Three experiments were performed on separate bags of gas with approximately the same M_0. In each experiment the length of the transverse sampling period T_{acq} was varied: **T_{acq}=4 ms, 256 ms, 512 ms**. The TR between RF pulses was fixed at 741 ms in all experiments with a nominal flip angle of 7°. T1 effects can be neglected due to the long sample T1's (>20 mins) and constant TR used throughout. The received ^{3}He signal was then fitted to $m_n = m_0(\cos\alpha)^{n-1}\sin\alpha$, where m_n is the detected transverse magnetization after the *n*th excitation and m_o is the initial transverse magnetization. This is an established means of calibrating α in HP gas NMR [3] –for a constant α the log curve, $\ln(m_n/m_0)$ should yield a linear slope of $\cos\alpha$.. The procedure was then repeated on the spherical ^{3}He cell.

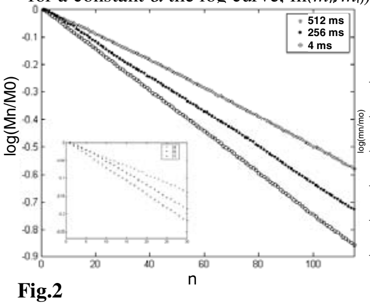

Fig.2

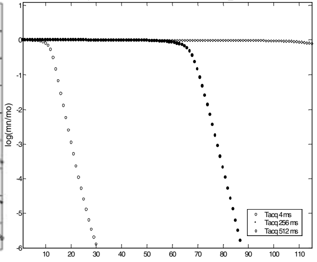

Fig.3

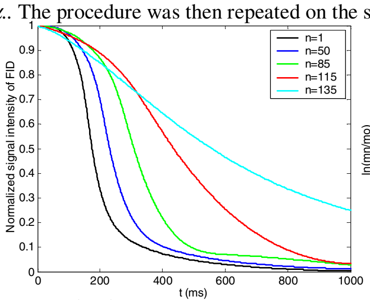

Fig. 4

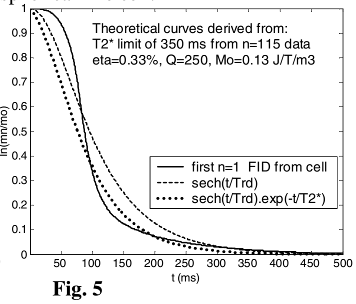

Fig. 5

Results and Discussion **Fig.2** demonstrates the effect of radiation damping in the bag phantom through use of **different T_{acq},** $\ln(m_n/m_o)$ is plotted for: (a) 512 ms, (b) 256 ms and (c) 4 ms. The long Tacq curves deviate from linear behaviour in the early stage –see inset. Apparent flip angles, α , were fitted from the linear regions and found to be **5.8°, 6.5° and 7.0°** respectively, indicating that more magnetization is returned to the longitudinal direction (more radiation damping has occurred) when the transverse magnetization is given a longer time to interact with the coil by a long T_{acq}. These findings are consistent with those observed with HP ^{3}He at B_0= 0.2T using a high η and high Q small pickup coil [4]. **Fig.3** shows the corresponding curves from the high M_0 cell sample, all three Tacqs show significant deviation from linear behaviour indicating a transient damping response as a function of the M_0. The T_{acq} =512 ms data in particular shows very little decay between RF pulses indicating very little consumption of the longitudinal magnetization and thus severe radiation damping. **Fig.4** shows the FID's acquired from the cell with T_{acq}=512 ms with *n*=1:135 pulses with transverse spoiling between pulses. As *n* increases, M_0 slowly decreases due to the non-recoverable spin population (Fig. 3). Hence radiation damping gradually diminishes, and this is manifested as a reduced damping of the acquired transverse signal –seen as an increasing relaxation time of the FID envelope. This is in agreement with experiments with water at 6.5T [3]. At n>135, noise becomes visible and the FID reaches a constant shape indicating radiation damping is negligible, with $T_2^* \approx 350$ ms. This corresponds to a spectral peak of <1 Hz with the well shimmed spherical sample. With this spherical sample we can discount confounding effects that might distort the FID, such as off resonance and dipolar demagnetizing field effects due to sample asymmetry, which can produce unexpected spin echoes and FID distortion [8]. **Fig. 5** shows attempts to fit the *n*=1 FID to **(i)** $sech(t/\tau_{rd})$ and **(ii)** $sech(t/\tau_{rd}) * \exp(-t/T_2^*)$ using the notation of Gueron [3] with T_2* estimated as 350 ms from the *n* =115 FID. The FIDs are clearly not pure *sech* or exponential functions, an accurate determination of the damped relaxation will require solution of the coupled differential equations of the Bloch equations with an appropriate radiation damping term. Nevertheless the second expression for the FID line-shape yields an estimate of **η=0.33%** which lies between our estimate from EM theory, 0.085%, and the geometrical upper limit, 3.6%.

Conclusion To our knowledge this is the first report of radiation damping in a birdcage resonator with samples hyperpolarized or otherwise. The presence and diagnosis of radiation damping in HP gas MR has major implications in RF calibration experiments in HP gas MRI, where accurate knowledge of the flip angle is imperative. The low η of the birdcage design (η estimated as <1 % for this coil) could explain why radiation damping effects have not been observed before in thermally polarised birdcage experiments with other nuclei. As the γ^1H is 4/3 larger than γ^3He, and the thermal M_0 of a standard 1 *l* water phantom is comparable to that used in the HP ^{3}He bag samples, then it would seem that the only factor inhibiting the observation of radiation damping in ^{1}H MRI with birdcage resonators are sample losses, which are non-existent with our low pass resonator and gas phantom.

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