# Inversion recovery in the presence of radiation damping - implications for evaluating contrast agents

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## Introduction

Relaxation measurements performed at high magnetic field may be adversely affected by the influence of radiation damping (RD) in concentrated samples such as $^1H$ in water or for highly non-equilibrium systems such as hyperpolarized $^{129}Xe$ and $^3He$. Radiation damping occurs when the large bulk transverse component of the magnetization of the sample induces a current in the RF coil that in turn drives the system back to equilibrium. This non-linear phenomenon can lead to chaotic dynamics that are no longer predicted by the conventional theory of NMR for dilute spin-systems. We consider how the measured value of $T_1$ is affected by this phenomenon for a gadolinium-doped water sample and for an un-doped water sample and consider the implications for evaluating contrast agents. Currently there is a huge expansion in the development of novel contrast agents, taking advantage of the advances in understanding of molecular mechanisms of disease. These include labelled iron-oxide particles, and caged gadolinium compounds that become active only when a certain reporter gene is expressed. Early stage development and evaluation of the efficacy of these agents depends on their effect on the relaxation time constants of water, often measured in experimental MR systems at high magnetic fields.

A simple method involving the application of a pulsed field gradient to de-phase transverse components of the magnetization is shown to be an effective method for suppressing this effect. Validation of this methodology has been carried out by measuring the relaxivity of a commercial contrast agent, GdDTPA. Given the central role that measurement of the $T_1$ of water plays in the assessment of contrast agents (1) as well as a host of other MR applications, care should *always* be employed when measuring and interpreting $T_1$ measurements at high magnetic fields.

## Theory and Methods

The recovery of the longitudinal magnetization to equilibrium becomes multiexponential in the presence of radiation damping, given by (2)

$$dM_z/dt = (M_z^{eq} - M_z)/T_1 + (M_x^2 + M_y^2)/M_z^{eq}T_{RD}, \qquad [1]$$

and has the effect of accelerating the recovery of the magnetization in a non-linear fashion that is proportional to the square of the magnitude of the transverse components of the magnetization with a radiation damping time-constant given by (3)

$$T_{RD} = 1/2\pi\eta Q M_z^{eq}\gamma \qquad [2]$$

where $\eta$ and $Q$ are the filling and quality factors of the coil, respectively, and $\gamma$ is the gyromagnetic ratio.

The proposed pulse sequence for measuring $T_1$ with suppression of radiation damping includes a pulsed field gradient applied for the entire duration of the inversion time with an amplitude of 5 $mTm^{-1}$ given by (180° - G - 90° - fid) where G denotes the gradient duration. Experiments were carried out on a Bruker DRX 500 MHz spectrometer equipped with a BBO probe at 298 K.

## Results and Discussion

Figs 1 and 2 show representative inversion recovery curves in the presence (filled symbols) and absence (open symbols) of radiation damping for two different water samples (4). In the absence of radiation damping the recovery curves become mono-exponential. For a 95% $H_2O$/ 5% $D_2O$ sample the relaxation time was found to be $T_1$ = 3.3 s whereas for a water sample containing 0.1 % w/v Magnevist (GdDTPA) the relaxation time was $T_1$ = 459 ms.

Relaxivity of a particular agent is defined as the increased relaxation rate of water per mole of added relaxation agent. We have assessed the validity of our method by studying the relaxivity of the standard contrast reagent GdDTPA. Fig. 3 shows the measured $T_1$ of water in the presence of different concentrations of [Gd] and with suppression of radiation damping. The relaxation rate is found to be linear with [Gd] and the relaxivity is calculated to be 4.36 $mM^{-1}s^{-1}$. This is consistent with published data for GdDTPA of 4.3 $mM^{-1}s^{-1}$ (1).

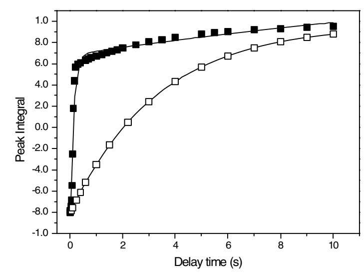


Fig 1. Inversion recovery applied to a sample of 95% $H_2O$/ 5% $D_2O$.

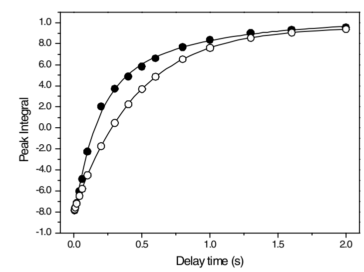


Fig 2. Inversion recovery applied to a brain functional imaging phantom containing 0.1 % w/v GdDTPA.

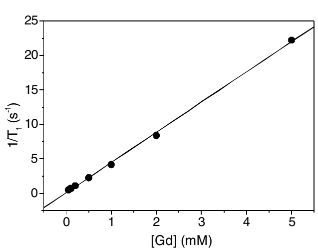


Fig 3. Relaxation rate of water as a function of [Gd] at 500 MHz and with suppression of radiation damping.

## Conclusions

We have demonstrated a method for the measurement of $T_1$ in highly polarized spin systems such as water that display the effect of radiation damping. This technique has been validated for a well-characterised contrast agent (GdDTPA) and can be used to assess novel contrast agents in magnetic resonance.

## Acknowledgements

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## References

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