Z-spectral Asymmetry Caused by Radiation Damping

J. Narvainen[1], D. C. Williamson[1,2], R. A. Kauppinen[3], G. A. Morris[1]
[1]School of Chemistry, University of Manchester, Manchester M13 9PL, United Kingdom, [2]Department of Chemistry, University of York, York YO10 5DD, United Kingdom, [3]School of Sport & Exercise Sciences, University of Birmingham, Birmingham B15 2TT, United Kingdom

Introduction: The asymmetry of Z-spectra can be used to study pH-dependent exchange processes *in vivo* (1). In radiation damping (RD) (2), an interaction between coil and sample, transverse magnetization M_{xy} generates a secondary radiofrequency magnetic field. Here we show that RD unexpectedly causes Z-spectrum asymmetry at high B_0 through an interaction with probe tuning. This effect may potentially complicate pH mapping methods which rely on Z-spectral asymmetry.

Theory: RD can be analyzed by adding feedback terms to the Bloch equations (3); in the general single-pool case they become

$$\frac{dM_x}{dt} = -\beta M_x - \delta M_y - k_d M_x M_z \cos^2\theta - k_d M_y M_z \cos\theta \sin\theta,$$

$$\frac{dM_y}{dt} = -\beta M_y + \delta M_x - \omega_1 M_z - k_d M_y M_z \cos^2\theta_z + k_d M_x M_z \cos\theta \sin\theta$$

$$\frac{dM_z}{dt} = -\alpha\left(M_z - M_0\right) + \omega_1 M_y + k_d (M_x^2 + M_y^2)\cos^2\theta$$

where $\alpha = 1/T_1$, $\beta = 1/T_2$, ω_1 = RF amplitude, and k_d determines the magnitude of the RD field. The phase angle for an LCR circuit $\theta = \tan^{-1}\left[Q\delta(2+\delta)/(1+\delta)\right]$ depends on the deviation $\delta = (\omega - \omega_0)/\omega_0$ from probe resonance, where Q is the probe quality factor, ω_0 the electrical resonant frequency and ω the RF frequency used. Because probe tuning is usually carried out by minimizing reflected RF power, in a typical "well-tuned" probe θ lies in the range ±15°. In Z-spectroscopy, water signal saturation by low-power RF is measured as a function of irradiation frequency ω. Magnetization exchange between water and labile protein sidechain protons causes a drop in water signal when ω_1 matches their Larmor frequency. A convenient measure of the effect is the Z-spectrum asymmetry $A(\omega)=S(-\omega)-S(\omega)$, where ω=0 for the water resonance. Accurate experimental determination of $A(\omega)$ requires interpolation between spectral data points.

Methods: NMR experiments were carried out on a Varian INOVA 400 spectrometer. Z-spectra were acquired using 20 s irradiation with $\gamma B_1/2\pi$ = 24 Hz and read flip angle 10º. T_1 and T_2 relaxation times of water were measured separately. Samples used were H_2O (1-pool model) and 0.4 M urea (2-pool model) in phosphate buffer (pH 7), each containing 10% D_2O, in 5 mm NMR tubes. The Bloch equations for 2-pool exchange with RD were solved and data interpolated using Mathematica.

Results and Discussion: At electrical resonance, the effect of RD is to narrow the Z-spectrum, but even slight detuning produces a dramatic asymmetry peak (Fig. 1). The narrowing arises because at electrical resonance the RD field opposes B_1 and is strongest where M_{xy} is greatest, on the flanks of the Z-spectrum dip. The asymmetry arises because the deviation from orthogonality between M_{xy} and the secondary RF field gives a handedness to the perturbation of the net RF field. In the spectrometer used the tuning error at minimum reflected RF power is 0.25 MHz, corresponding to θ = 12° for the coil Q of 210. At given tuning offset, the position and size of the RD-peak in asymmetry depend on relaxation (short T_1 narrows the Z-spectrum), ω_1 (high ω_1 broadens the Z-spectrum) and k_d (strong RD increases the peak amplitude).

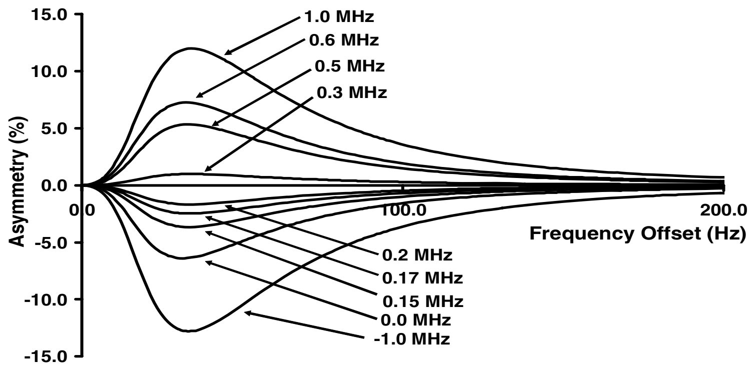

Figure 1: M_z/M_0 for different electrical tunings, 1-pool sample (H_2O)

In the urea sample (Fig. 2), the effects of RD on asymmetry of Z-spectra are of same magnitude as those of exchange, and RD changes the amplitude of the exchange peak by up to 10%. The effects would be more serious for species resonating closer to H_2O, for stronger damping, and for higher ω_l. In our system the damping field $k_d M_0/\pi$ was 47 Hz for H_2O, and 42 Hz for the urea sample. In *in vivo* experiments RD is usually weaker, but so are the pH-dependent changes being studied.

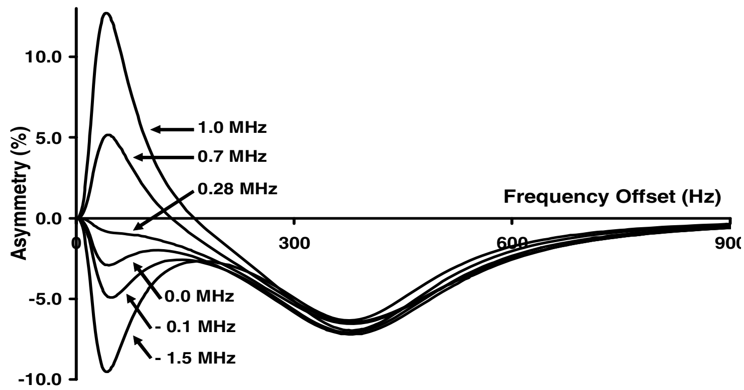

Figure 2: M_z/M_0 for different electrical tunings, 2-pool sample (0.4 M urea)

Conclusions: We have shown that RD causes asymmetry in Z-spectra unless the coil is at exact electrical resonance. RD may affect *in vivo* applications of magnetisation transfer techniques and complicate the determination of pH via Z-spectroscopy at high B_0 using high Q coils.

Acknowledgements: Supported by the Sigrid Juselius Foundation, the Academy of Finland and the Leverhulme Trust (grant F00120Y).

References: 1) Zhou et al., Nat Med 9 1085, 2003 2) Suryan: Curr Sci. 18 203 1949 3) Barjat et al., J. Magn. Reson. A 117 109 1995