MR Spin Behavior During RF Pulses: T2 vs. T2' Relaxation

M. Carl[1], N. Szeverenyi[2], M. Bydder[2], E. Han[1], and G. Bydder[2]
[1]GE Healthcare, Waukesha, WI, United States, [2]University of California, San Diego

Introduction: We investigate the behavior of the MR magnetization vector during RF pulses in the presence of rapid transverse relaxation. The transverse relaxation is divided into two separate mechanisms: Homogeneously broadened lines which resulting in irreversible T_2 amplitude decay, and inhomogeneously broadened lines resulting in dephasing and in principle refocusable T_2'. While the two different mechanisms by themselves result in identical free induction decay (FID) behavior, it is shown they do not follow the same magnetization trajectory during the application of external RF pulses. Therefore, RF optimization strategies based solely on the classical Bloch equations [1-3] may benefit from additional modifications described here when imaging species with high inhomogeneously broadened linewidths (for example due to susceptibility effects) as found in bone.

Theory: On a microscopic level the decay of transverse magnetization in MR can be described as collective spin dephasing resulting in a line broadening of the MR resonance frequency. In liquids, the mean dipolar fields from nearby rapidly and randomly moving and tumbling molecules average to zero, and the overall loss of coherence is reduced, leading to the characteristically long T_2 of liquids. Since the correlation time of the random dipolar interactions in liquids is very short (sub-nanoseconds), the signal coherence cannot be refocused using RF refocusing pulses on clinical MRI scanners Therefore, it can be modeled as an irreversible amplitude loss of the transverse magnetization, which corresponds to the T_2 decay described in the classical Bloch equation. The broadening of the linewidth due to such irreversible amplitude loss is also called “homogeneously broadened linewidth”. In the other limit of static magnetic field interactions (called “inhomogeneously broadened linewidth”, e.g. caused by magnetic susceptibility) the dephasing builds up continuously, leading to additional decay (T_2'). These static interactions do not average away as do the fast random dipolar interactions in pure water, consequently they can be “refocused” using a spin echo pulse. An illustration of the amplitude and dephasing model is shown in Fig.1.

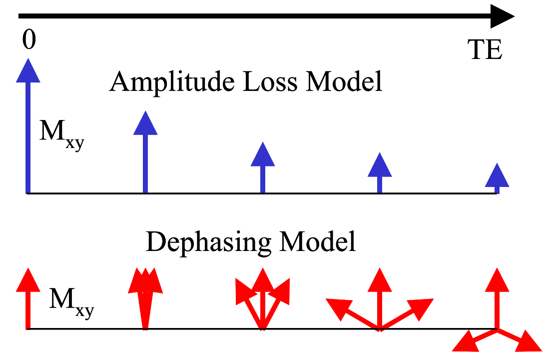


Fig.1: Illustration of transverse magnetization decay as a function of increasing TE.Amplitude loss model (top) which is mathematically described by the classical Bloch equations. Dephasing model (bottom) relevant for static field inhomogeneities resulting in T_2* decay.

Bloch Simulations: T_2* was modeled as a combination of reversible dephasing (T_2') using a Lorentzian distribution of resonance frequencies (ω) and irreversible signal decay (T_2) using a simple exponential amplitude loss. The MR signal was calculated from:

$$S(t)=\frac{1}{\pi T_2'}\exp\left(-\frac{t}{T_2}\right)\int_{-\infty}^{\infty}\frac{S(t,\omega)}{\omega^2+\left(1/T_2'\right)^2}d\omega \rightarrow \frac{1}{\pi T_2'}\exp\left(-\frac{t}{T_2}\right)\sum\frac{S(t,\omega)}{\omega^2+\left(1/T_2'\right)^2}\Delta\omega \qquad \text{with} \qquad \frac{1}{T_2^*}=\frac{1}{T_2}+\frac{1}{T_2'} \qquad (1)$$

where S(t,ω) is the simulated signal using Bloch equations for a given ω within the Lorenzian distribution at time t. To confirm the validity of this model, we first simulated a simple spin echo sequence with an idealized (i.e. short) RF refocusing pulse at 1ms. We used a fixed T_2* of 1ms with three distinct values of T_2' of 1.33ms, 2ms, and 4ms (corresponding to the three distinct Lorentzian lineshapes in Fig.2a). As shown in Fig.2b, the simulated signal evolution before the refocusing pulse (vertical line) follows the same free induction decay for all three curves. Furthermore, the signal evolutions after the refocusing pulse generate the expected spin echo behaviors, therefore confirming the validity of the simulation model.

Using this simulation model, the magnetization behavior during a single hard RF pulse with constant amplitude of B_1 = 25μT and nominal flip angle of θ = 180° is shown in Fig.3 for several values of T_2*. For each value of T_2*, we simulated both the pure amplitude decay model (thin lines) and pure dephasing model (thick lines). The time evolution of the longitudinal vs. transverse magnetization corresponds to an inversion only for the limiting case of $T_2 \rightarrow \infty$ and the maximum transverse signal is not achieved by a nominal 90° pulse (markers) but rather with a smaller flip angle. For finite values of T_2 the two models show deviations in the magnetization trajectory. As can be seen from Fig.3, during an RF pulse, signal decay arising from an inhomogeneously broadened linewidth (thick lines) results in less transverse magnetization than signal decay arising from a homogeneously broadened linewidth (thin lines).

The longitudinal and transverse magnetization generated by a single RF pulse (e.g. from Fig.3) can be combined to determine the steady state SPGR signal generated by a SPGR RF pulse train (see for example [2]). From the SPGR signal one can determine the optimum values of the RF pulse duration and therefore flip angle, which is shown in Fig.4 as a function of T_2* for both models at several values of TR/T_1. As expected, the two models converge to the values of the classical Ernst angle in the limit of long T_2. The deviation between the two models is most pronounced for short T_2 and longer TR where the optimum flip angle can be up to 50% smaller for the dephasing model than for the amplitude loss model.

Conclusion: We have investigated the behavior of the MR magnetization vector during RF pulses in the presence of rapid transverse relaxation caused by either amplitude loss or spin dephasing. We found that different tissues with the same T_2* may generate different responses to RF pulses, dependent on whether the relaxation is dominated by a homogeneously or inhomogeneously broadened linewidth. In vivo tissues usually have contributions from both homogeneously and inhomogeneously broadened lines. Complete RF optimization in the presence of rapid transverse relaxation may hence require explicit knowledge of the intrinsic T_2 and T_2* of the tissue. This may play a particularly important part in tissues containing high susceptibility background fields such as imaging around metal implants.

References: [1] Tyler et al, JMRI 25:279 (2007) [2] Carl et al, *ISMRM* 2009, p.4343 [3] Carl et al, *ISMRM* 2009, p.4375

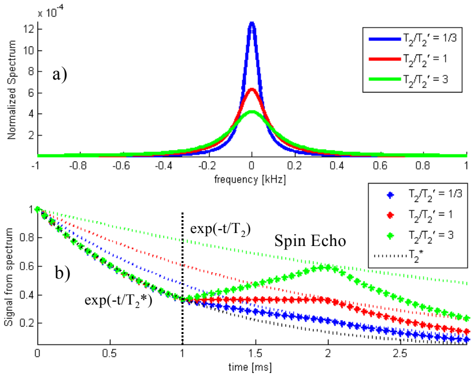
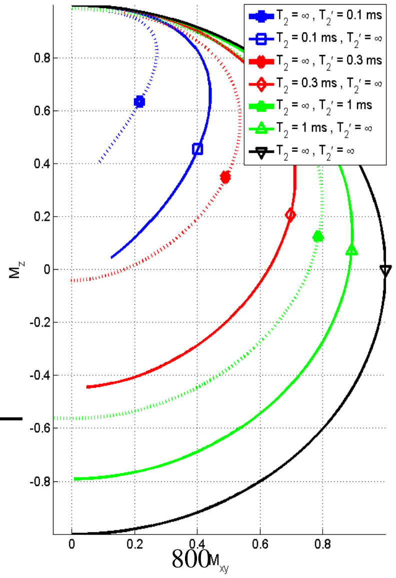


Fig.2: Lorentzian lineshapes and corresponding simulated signals to model T_2* decay.

Fig.3: Time evolution of longitudinal vs. transverse magnetization for a single hard RF pulse with a fixed B_1 = 25 μT, and a nominal flip angle going from 0 to 180°. The dephasing model is shown as broken lines, while the amplitude loss model is shown as solid lines. The nominal 90° excitation points are denoted by the distinct makers on the curves.



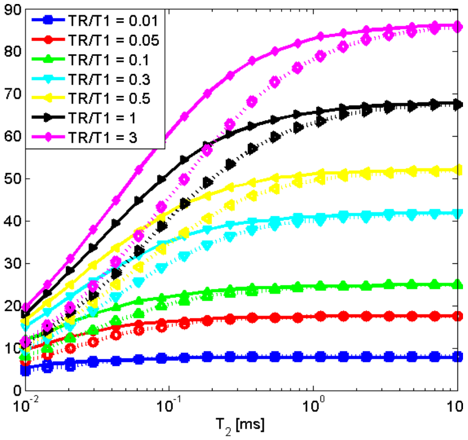


Fig.4: Optimum flip angle of a hard RF pulse train (B_1 = 25μT) as a function of T_2. The dephasing model is shown as broken lines, while the amplitude loss model is shown as solid lines.