diffusion-fundamentals

The Open-Access Journal for the Basic Principles of Diffusion Theory, Experiment and Application

Split 180° Sequences

Denise E. Freed,[1] *Ulrich M. Scheven,*[2] *Martin D. Hürlimann*[1]

[1] Schlumberger-Doll Research, USA
[2] Dept. of Chemistry, FCT Universidade Nova de Lisboa, Portugal

Corresponding author: Denise E. Freed, Schlumberger-Doll Research, Cambridge, MA 02461, E-Mail: freed1@slb.com

(received 14 July 2008, accepted 1 March 2009)

Abstract

In applications of NMR in inhomogeneous fields, sequences based on the Carr-Purcell-Meiboom-Gill (CPMG) sequence play a central role. The standard CPMG sequence consists of an initial 90° excitation pulse, followed by a long string of 180° refocusing pulses. This creates a series of echoes that decay with characteristic relaxation time $T_{2\mathrm{eff}}$. Here we present a modified sequence, the *Split-180° sequence* that specifically takes advantage of grossly inhomogeneous fields. In its simplest implementation, the 180° refocusing pulse of the CPMG sequence is split into two separate pulses. This sequence, which can be viewed as a modification of the CPMG sequence, simultaneously generates two types of signal that can be separately detected. One is a CPMG-like signal that decays with the expected relaxation time $T_{2\mathrm{eff}}$. In addition, a second type of signal builds up and approaches a steady-state. The amplitude of this dynamic equilibrium depends on the ratio of the longitudinal to the transverse relaxation times, T_1/T_2. We present experimental results and summarize the new theory that describes both signals in a unified manner.

Keywords

CPMG, steady-state free precession, grossly inhomogeneous fields

1. Introduction

The CPMG sequence and sequences based on it are well-suited for measuring relaxation times in moderately inhomogeneous fields. As applications in grossly inhomogeneous fields become more common, the question arises as to whether the CPMG sequence is the most efficient type of sequence in those fields. In the CPMG sequence an initial 90° pulse is applied and is then refocused by a long series of 180° pulses. In between the 180° pulses, the signal refocuses to form an echo. The long train of 180° pulses can also be thought of as a steady-state free precession (SSFP) sequence. For this type of sequence, there is a single repeating pulse. After some time, the spins reach a steady state or dynamic equilibrium, and there is a signal before and after each pulse. When the space between pulses is much smaller than the relaxation times, the amplitude of these signals depends only on the properties of the

© 2009, D. Freed

spins through their total magnetization M_0 and the ratio between the longitudinal and transverse relaxation times T_1/T_2. In extremely inhomogeneous fields, though, the signal is almost entirely obscured by the pulse.

Here we propose a new sequence, the split 180° pulse sequence. In this sequence, the 180° pulses are divided into two 90° pulses, as shown in Figure 1. The entire repeating unit has a duration of t_R. This sequence will still have a CPMG-like signal because the pair of 90° pulses will refocus spins, similarly to the 180° refocusing pulses. In inhomogeneous fields it will also have a steady-state signal due to the repeated application of the two 90° pulses.

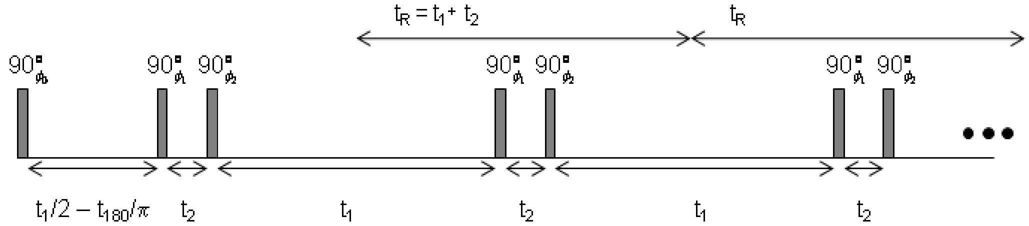

Fig. 1: Split-180° pulse sequence.

1.1 Theory

The CPMG signal at time $t = k\, t_R$ comes from summing over all the coherent pathways that are of length t. It is given by [1]

$$\vec{M}_{CPMG}(kt_R) = \left(\vec{M}(0^+)\cdot\hat{n}\right)\hat{n}\exp\left\{-kt_R / T_{2,CPMG}\right\}, \qquad (1)$$

where $M(0^+)$ is the transverse magnetization just after the initial 90^o pulse, $\hat{n}$ is the axis of the composite rotation, and $1/T_{2,\mathrm{CPMG}}$ is an effective relaxation rate, which is the sum of $1/T_1$ times the amount of time the spins are along the z-axis and $1/T_2$ times the amount of time the spins are in the x-y plane.

The SSFP signal at time t comes from summing over all coherent pathways that are of length 0, t_R, $2t_R$, $3t_R$, ... up to t. Thus there will be many contributions to it because the shorter paths will not have decayed very much. The signal from these coherent pathways can be calculated by methods similar to those in Ref. [2]. When t_R is much less than the relaxation times, it is given by

$$\vec{M}_{dyn}(kt_R) = M_0 \frac{T_{2,eq}}{T_1}(\vec{\rho}\cdot\hat{n})\,\hat{n}\left(1-\exp\left\{\frac{-kt_R}{T_{2,eq}}\right\}\right), \qquad (2)$$

where M_0 is the equilibrium magnetization of the spins, $M_0\vec{\rho}\, t_R / T_1$ is the fresh coherent magnetization that has arisen during t_R due to relaxation along the z-axis, and $\hat{n}$ and $T_{2,\mathrm{eq}}$ are defined as for the CPMG signal. This signal will grow to the steady-state or dynamic equilibrium signal. The vectors $\vec{\rho}$ and $\hat{n}$ are independent of relaxation times, so that $M_{\mathrm{dyn.eq}}$ depends on T_1 and T_2 only through the ratio T_1/T_2. We note that the expressions (1) and (2) are quite general and will hold for similar pulse sequences with an arbitrary repeating unit. The steady-state signal will also depend strongly on diffusion, because the higher-order coherent pathways, which are sensitive to diffusion, contribute significantly to the signal.

2. Results

The experimental set-up was the same as in previous work on grossly inhomogeneous fields [3]. The samples were placed in a fringe field and were subject to a magnetic field

© 2009, D. Freed

with a Larmor frequency of 1.750 MHz and a static gradient of 13 G cm^{-1}. In Fig. 2 the echo shapes for the CPMG-like signal and the SSFP signal are shown. For this data, t_1 = 568 μs and t_2 = 92 μs and the two 90° pulses both have a phase of zero. The interval shown is the interval during t_1, and the two pulses occur at $t = \pm 284$ μs. Because the CPMG-like signal depends on the phase of the initial pulse and the SSFP signals does not, the two signals can be separated by phase cycling. As can be seen in the plot, there is still a CPMG-like signal, although now it is broken up into several echoes. The asymptotic form of the SSFP echo is given in the second plot. There are now easily observable echoes between the two 90° pulses. In both cases, there is excellent agreement between the theoretical echo shapes and the measured ones.

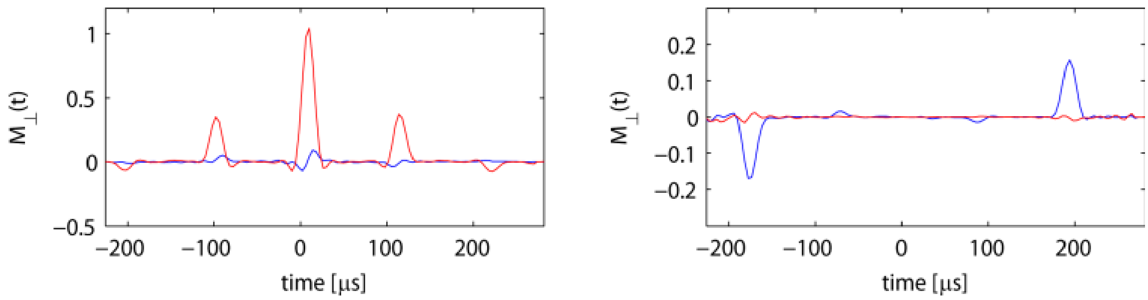

Fig. 2: Echo shape of the CPMG-like signal (left) and the dynamic equilibrium signal (right).

Figure 3 shows the time dependence of the amplitudes of the CPMG-like signal and the dynamic equilibrium signal. As expected, the CPMG-like signal decays to zero with T_2. The dynamic equilibrium initially rises and then remains at a constant value. The fits to the theory with a single time constant are shown in black.

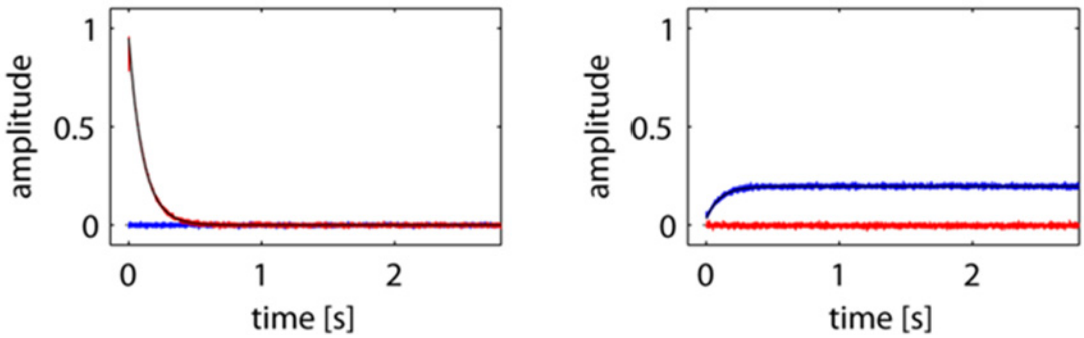

Fig. 3: Experimental results of the split-180° sequence on a sample of doped water with a relaxation time $T_1 = T_2$ of 100 ms. The left panel shows the amplitudes of the CPMG-like signal, and the right panel displays the amplitudes of the dynamic equilibrium signal.

3. Conclusions

The split 180° sequence generates both a CPMG-like and a SSFP signal, which are easily detected and from which M_0, T_2 and T_1/T_2 can be found. The constant long-time amplitude of the SSFP signal improves signal averaging and the detection of components with short values of T_2. This sequence obtains signal from spins with a large range of offset frequencies, so it works well in grossly inhomogeneous fields.

References

[1]M.D. Hürlimann and D.D. Griffin, *J. Magn. Reson.*, **143** (2000) 120-135.
[2]E.T. Jaynes, *Phys. Rev.* **98** (1955) 1099-1105.
[3]M. D. Hürlimann, *J. Magn. Reson.*, **148** (2001) 367-378.

© 2009, D. Freed