# Feasibility of extracting quantitative measurements of $T_2$ and diffusion using sequences based on the Burst concept

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## Introduction

Burst [1] was originally suggested as a single-shot ultra-fast imaging sequence. However, the ability to acquire a large number of echoes after a single excitation period leads to the possibility of obtaining quantitative data, weighted primarily by diffusion and $T_2$. A potential advantage over other methods is the use of many echoes to analyse multi-exponential decays. Hennig [1] hinted that it might be possible to use a variant of the sequence in order to measure diffusion coefficients, while Doran and Décorps [2] demonstrated that a simultaneous measurement of $D$ and $T_2$ was possible in a single-shot for bulk samples. This worked well only if a small elementary flip angle was used in the Burst pulse train. A natural adaptation of that method to the imaging context has previously been presented [3]. A generic problem with all Burst sequences is a low signal-to-noise ratio (SNR) due to the low excitation flip angle, $\alpha$. In order to obtain images with adequate SNR, one must increase this angle significantly above that recommended in [2]. The current work investigates to what extent this is feasible whilst maintaining quantitative accuracy.

## Theory

A Burst excitation pulse train is simply a set of $n$ pulses of flip angle $\alpha$, with periods of constant read-dephasing between them. Its effect on the sample magnetisation may be described by Hennig's phase graph algorithm. Every pulse splits the magnetisation into three separate pathways. In general, a possible $3^{n-1}$ different echoes are possible, but in Burst, many of these echo pathways coincide, leading to echo amplitudes that are weighted according to different functions of $\alpha$, $T_1$, $T_2$ and $D$. The results simplify greatly in the so-called linear approximation (or small-angle limit) and it is possible to fit the data to derive values for $T_2$ and $D$. A number of groups (e.g., [4]) have demonstrated that by an appropriate phase-modulation of the excitation pulse it is possible to increase substantially the available SNR, but the consequences of this modification for accurate quantitative measurement have not so far been investigated.

## Methods

The echo amplitudes obtained from a Burst experiment may be calculated either by the partition method of Kaiser *et al*. [5], or by using Hennig's transition matrix formalism [1] or by direct Bloch simulation. The latter method gives additional insight into the spatial profile of the excited magnetisation and so was used here. For reasons of space, this abstract will be restricted to the quantitative analysis of $T_2$, but the same methods are equally applicable to diffusion or combinations of the $T_2$ and $D$. A spin-echo Burst sequence, consisting of 9 $\alpha$-pulses, phase-modulated according to [4], and separated by 10 ms, followed by a 180° and refocusing period, was simulated for hypothetical ($D = 0$) samples with different combinations of $T_1$ and $T_2$. $\alpha$ was varied between 0° and 30° and a standard $T_2$ decay model fitted to the data. In a second computational experiment, the sample had a bi-exponential decay and the ability of the sequence to give data suitable for extracting the two components was investigated for different flip angles. In each case, noise was added to the data at different levels.

## Results and Conclusion

Fig. 1 shows the raw, noise-free, simulation data for a sample with $T_1 = 1$ s and $T_2 = 100$ ms. A clear difference may be seen between the cases where $\alpha = 0.1°$ (linear approximation) and 22° (max. value allowed in [4] for 9 pulses). All the points are higher, because some of the contributing magnetisation spends time along the longitudinal axis. Fig. 2, simulated with Gaussian noise of 1% maximum signal, shows how, as $\alpha$ increases, the relative error in $T_2$ determination goes up dramatically (high values are clipped at 50%). In addition, it can be seen how, for larger $\alpha$, the quality of the result is strongly dependent on the value of $T_2$ being fitted. Fig. 3 shows the affect of the Burst pulse angle $\alpha$ on the determination of the long and short components for a simulated bi-exponential sample ($T_{2\text{short}} = 0.05$ s, $T_{2\text{long}} = 0.3$ s) with the same noise as in Fig. 2. It can be seen again that the error in determination of $T_2$ rises dramatically with increasing pulse angle. The conclusion is thus that, although the pulse modulation schemes can increase SNR in an imaging context, $\alpha$ must still be restricted to small angles for quantitative work. This limitation suggests that the future for Burst in these areas will be more limited than previously envisaged.

## References

[1] Hennig, *MAGMA* **1**, 39 (1993); [2] Doran, *JMR A* **117**, 311 (1995); [3] Wheeler-Kingshott, *MRM* **44**, 737; [4] Zha, *MRM* **33**, 377;
[5] Kaiser, *J Chem Phys* **60**, 2966

**Figure 1**

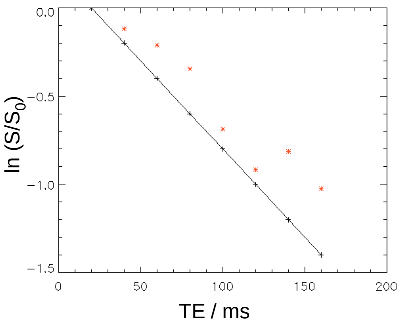

**Figure 2**

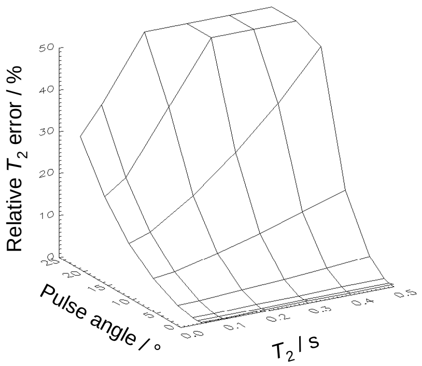

**Figure 3**