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T_2 Selectivity: Comparison between Different Kinds of RF Pulses

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Techniques allowing characterization of specific T_2 species are used to perform MR imaging of structures whose signal intensity is poor on conventional methodologies. T_2-selective pulses can be used to discriminate signals from tissues with different T_2 values. In case of soliton pulses, the magnetization from all the T_2 species is inverted, with the exception of specific T_2 structures which have both the longitudinal and the transverse magnetization nulled on resonance. Solitons have the drawback of being very long even if the selected T_2 value is in the order of tens of milliseconds. The aim of this paper is to examine whether it is possible to use pulses shorter then solitons keeping their T_2 selectivity, that is keeping null longitudinal magnetization, while accepting some residual transverse magnetization for structures with the selected T_2. Different kinds of inversion pulses were generated, all to select the same T_2 species. Pulses performance was analyzed by studying the dependence of the residual transverse magnetization on resonance from the length of the pulse. An exponential relationship between transverse magnetization and pulse length was found, which was not dependent on the pulse type.

INTRODUCTION

In T_2-weighted MR imaging, tissues characterized by long transversal relaxation time (T_2) are highlighted. Nevertheless, in some applications the examination of structures with short T_2 is required. Tissues with specific T_2 values can be emphasized by using RF pulses which selectively excite or saturate them.

A long suppression pulse is used to improve the contrast between short- and long-T_2 species (*1, 2*). A T_2-dependent suppression of magnetization is also performed in magnetization transfer (MT) imaging (e.g. (*3, 4*)).

The selection of tissues with specific T_2 values can be possibly improved by T_2-selective pulses. These pulses have been designed by taking into account the relaxation time effects.

The generation of RF pulses is a solved problem when the relaxation effects are neglected (*5–8*). In particular, the inverse scattering transform (IST) (*9*) has been proved to be a very efficient method. It reduces the Bloch equation to a 2×2 scattering problem (Shinnar–Le Roux approach) (*10, 11*). This system can be inverted to provide the RF pulse needed to obtain a given magnetization response.

Recently, Rourke and Bush (*12*) proved that the IST technique can be successfully used to invert the Bloch equations without neglecting relaxation effects. They showed that by IST it is possible to calculate the so-called T_2-selective pulses which select structures with given T_1 and T_2 values by nulling both the longitudinal and the transverse magnetization.

Structures with much shorter T_2 are unaffected, whereas the magnetization of structures characterized by very large T_2 is inverted. These pulses, also called *solitons,* are not easy to use in practice because in order to select samples with T_2 in the order of tens of milliseconds, a pulse length of hundreds of milliseconds is needed.

If some residual magnetization can be tolerated, every pulse which inverts the longitudinal magnetization from structures with very long T_2 values can be considered T_2 selective for a specific T_2 value.

In this paper, the behavior of different inversion pulses—solitons, rectangular, gaussian, and sinc pulses—has been studied by examining the relationship between residual transverse magnetization and pulse length.

METHODS

Assuming an infinite T_1 value, the general form of the simplest nontrivial real soliton is

$$B_1(t) = \frac{a_1}{|a_1|} \frac{2}{T_2(e^{-\tau/T_2} + e^{\tau/T_2})}, \qquad [1]$$

where $a_1 \in R$, $\tau = t/T_2 - \ln(|a_1|)$, and $-\infty < t < \infty$ (*12*). In our simulation, the parameters T_2 and a_1 have been set to 20 ms and 1, respectively.

In order to use solitons both in simulations and in MR sequences, the pulse must be cut. The criterion used in this paper is to fix the amount by which the pulse differs from zero at its tails (*accuracy*). Five accuracy values have been chosen: 10^{-4}, 10^{-3}, 10^{-2}, $2.1 * 10^{-2}$, and $2.9 * 10^{-2}$.

The effects of a nonvanishing pulse amplitude at the beginning and at the end of a pulse are often reduced by filtering the pulse in the time domain. All the solitons have been filtered by using Hanning filter and offset subtraction.

The Hanning filter lets the soliton tails decrease to zero,

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whereas its maximal amplitude does not change. By using the offset subtraction, the difference from zero at the pulse tails is removed from the original pulse. The maximum amplitude is therefore reduced.

Cutting and filtering change the T_2 selectivity of the pulses, which means that the longitudinal and transverse magnetization are no longer nulled for the given T_2 value. In order to obtain null longitudinal magnetization, the length of the modified pulse must be adjusted. The residual transverse magnetization was evaluated as a measure of the quality of the T_2 selectivity of the pulse.

Not only soliton pulses can be used to null the longitudinal magnetization of structures with a given T_2. All 180° pulses null the longitudinal magnetization on resonance for a specific T_2 value. If the length of the pulse changes, the T_2 value changes too.

We performed simulations with different inversion pulses changing their lengths to have null longitudinal magnetization for $T_2 = 20$ ms and then we examined the residual transverse magnetization on resonance.

A rectangular pulse has been used and gaussian inversion pulses with the same accuracy values used for solitons have been generated. All gaussian pulses have been filtered by Hanning filter and by offset subtraction and then examined together with nonfiltered gaussian pulses.

In order to study the behavior of pulses with negative sidelobes, a sinc pulse with seven lobes (sinc7) has been created. Other sinc pulses have been produced by cutting the sinc pulse with seven lobes, instead of fixing a tail accuracy. Five-lobe (sinc5), three-lobe (sinc3), and one-lobe pulses have been generated.

In order to make the rectangular, gaussian, and sinc pulses selective for samples with $T_2 = 20$ ms, their lengths had to be modified to several or hundreds of milliseconds. Pulses with lengths of more than 400 ms were not further analyzed, as the use of very long pulses is often restricted by hardware limitations. Furthermore, the residual transverse magnetization of very long pulses is too small to be calculated with appropriate accuracy by our simulation program.

The behavior of all pulses has been examined by studying the dependence of the amount of residual transverse magnetization from the length of the pulse. A regression line has been calculated using data from all pulses.

The correlation coefficient of the fit has been calculated. The significance of its value has been checked by means of two-tailed statistical hypothesis tests (null hypothesis: $\rho = 0$) with significance level $\alpha = 0.01$ (*13*).

The T_2 selectivity of all pulses has been studied by analyzing the longitudinal magnetization value on resonance as a function of T_2 (the following T_2 values have been used: 10,000, 1000, 500, 100, 50, 30, 20, 10, 5, 1, 0.5, and 0.1 ms).

Actually, it is not always possible to neglect T_1 effects. Therefore, the behavior on resonance of longitudinal magnetization from rectangular and sinc pulses with three lobes—respectively, the shortest and longest pulses—has been analyzed for three different T_1 values: $T_1 = 100 \times T_{2\_ref}$, $T_1 = 50 \times T_{2\_ref}$, and $T_1 = 10 \times T_{2\_ref}$, where $T_{2\_ref} = 20$ ms.

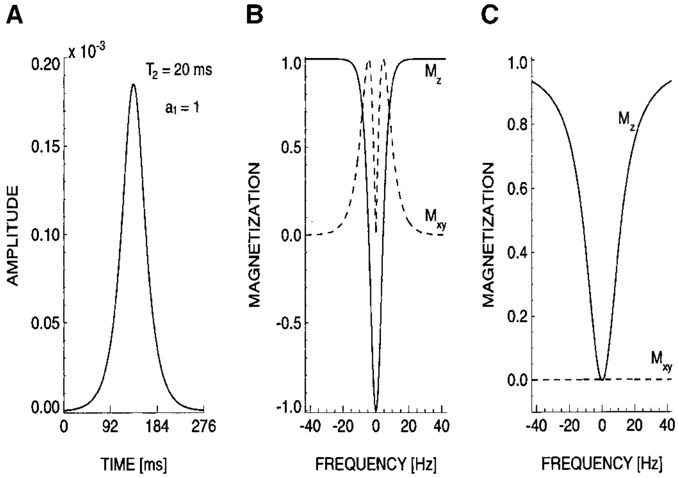

FIG. 1. Simplest nontrivial real soliton pulse calculated with $a_1 = 1$ and $T_2 = 20$ ms to be selective for spins characterized by a 20-ms T_2 value (A). The profiles of M_z (solid) and M_{xy} (dashed) from the soliton pulse are simulated for spins with $T_2 = \infty$ (B) and for spins with $T_2 = 20$ ms (C).

Simulations have been performed in order to study the effects of shortening on pulse full width at half maximum (FWHM) bandwidths. Indeed, the main aim was to check whether shortening could broaden the pulse bandwidth.

RESULTS

The soliton pulse calculated by using $a_1 = 1$, $T_2 = 20$ ms, and an accuracy value of 10^{-4} and the magnetization profiles simulated setting T_2 to infinity and to 20 ms are plotted in Figs. 1A–1C, respectively.

If T_2 is equal to infinity, there is full inversion on resonance, whereas in the second case when T_2 is equal to 20 ms both longitudinal and transverse magnetization are nearly zero.

The value on resonance of the longitudinal magnetization after the soliton pulse calculated with an accuracy of 10^{-4} has been plotted in Fig. 2 as a function of the logarithm in base 10 of T_2 normalized to the reference value $T_{2\_ref} = 20$ ms. The longitudinal magnetization is smaller than $\pm 10\%$ if T_2 runs in a range of $\pm 20\%$ of the reference value, that is 16 ms $< T_2 <$ 24 ms.

In Table 1 the lengths and the values on resonance of transverse magnetization from cut and filtered soliton pulses are presented. It is evident that a compromise between length of the pulse and amount of residual transverse magnetization must be made. The longer the pulse, the smaller the value of the transverse magnetization.

In order to make the rectangular pulse selective for spins with $T_2 = 20$ ms, its length has been adjusted to 85 ms. In Figs. 3A–3C, the rectangular pulse is shown with the magne-

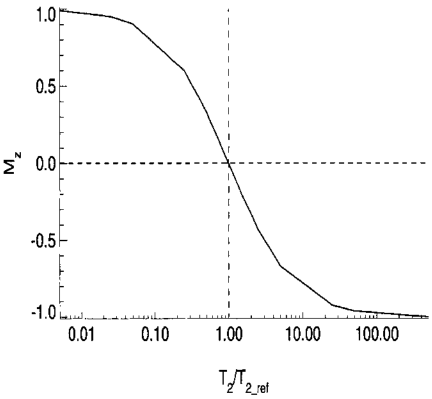

FIG. 2. Longitudinal magnetization versus T_2/T_{2_ref}, where $T_{2\_ref} = 20$ ms. On the x-axis, the logarithmic scale (base 10) is used. T_1 relaxation has been neglected.

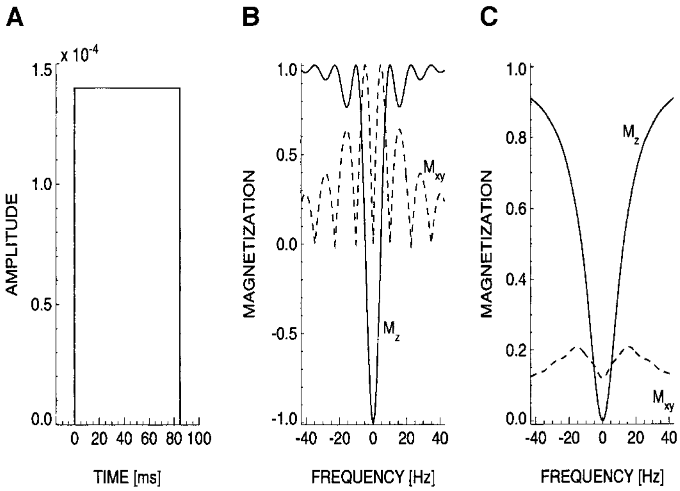

FIG. 3. Rectangular pulse 85 ms long (A) can be considered T_2 selective for spins characterized by a 20-ms T_2 value if some transverse magnetization can be accepted. The profiles of M_z (solid) and M_{xy} (dashed) from the rectangular pulse simulated for spins with $T_2 = \infty$ (B) and for spins with $T_2 = 20$ ms (C).

tization profiles from samples with $T_2 = \infty$ and $T_2 = 20$ ms. In the last case, there is 12% of residual transverse magnetization on resonance.

In Table 2, lengths and on-resonance transverse magnetization values of all the gaussian pulses are given. The results here presented corroborate with those found for solitons: the higher the accuracy, the longer the pulse and the smaller the residual transverse magnetization.

Filtering has been applied to sinc pulses with three lobes and one lobe. All sinc pulses have been adjusted to make them T_2 selective for $T_2 = 20$ ms. Modified lengths and residual transverse magnetization on resonance are presented in Table 3.

Once filtered and adjusted to make them T_2 sensitive for $T_2 = 20$ ms, all positive pulses turn out to be longer than the correspondent nonfiltered pulses.

Filtered sinc pulses with a number of negative sidelobes greater than the number of positive sidelobes (sinc3) are shorter than nonfiltered pulses. In particular, Hanning-filtered sinc3 is almost 100 ms shorter than sinc3.

In Figs. 4A–4C, the natural logarithm of transverse magnetization from all pulses has been plotted as a function of the pulse length. In order to make the pictures readable, the data had to be split into three parts, but the regression line shown in every figure has been calculated by using data from all pulses.

The correlation coefficient ρ of the fit has been calculated to be -0.9995. This indicates a strong linear relationship between the pulse length and the natural logarithm of residual M_{xy}. The correctness of the hypothesis has been proved by calculating the t-distribution value and comparing it to the critical value: $|t_\rho| = 187.007 \gg t_{35,0.01} = 2.724$ (*13*).

The T_2 selectivity of all pulses has been analyzed again studying the value on resonance of the longitudinal magnetization as a function of $\mathrm{Log}_{10}(T_2/T_{2\_ref})$. All soliton pulses, the rectangular pulse, and the gaussian pulses have on resonance the same T_2 selectivity as the soliton pulse cut with an accuracy of 10^{-4}. Sinc pulses with the exception of sinc1 have a different T_2 selectivity as shown in Figs. 5A–5D.

On resonance, T_2-selective pulses null the longitudinal magnetization for infinite T_1 and for $T_2 = 20$ ms. Effects due to noninfinite longitudinal relaxation ($T_1 = 2000$ ms, $T_1 = 1000$ ms, $T_1 = 200$ ms) have been analyzed studying the deviation from zero of the longitudinal magnetization.

At $T_1 = 2000$ ms, the 85-ms-long rectangular pulse induces a deviation from zero longitudinal magnetization of 2%, which

TABLE 1
Soliton Pulses T_2 Selective for Samples with $T_2 = 20$ ms

	Without filter		Hanning filter		Offset subtraction	
Accuracy	Length (ms)	M_{xy}	Length (ms)	M_{xy}	Length (ms)	M_{xy}
10^{-4}	276	0.001	320	0.0004	280	0.001
10^{-3}	189	0.009	243	0.002	201	0.007
10^{-2}	116	0.055	178	0.012	141	0.03
2.1×10^{-2}	99.5	0.083	161	0.018	127.5	0.041
2.9×10^{-2}	93.5	0.1	155	0.02	122	0.05

TABLE 2
Gaussian Pulses T_2 Selective for Samples with $T_2 = 20$ ms

	Without filter		Hanning filter		Offset subtraction	
Accuracy	Length (ms)	M_{xy}	Length (ms)	M_{xy}	Length (ms)	M_{xy}
10^{-4}	204.81	0.006	269.76	0.0012	240.43	0.0026
10^{-3}	169.74	0.015	243.14	0.0023	204.45	0.006
10^{-2}	125.76	0.046	209.6	0.0051	136.7	0.032
2.1×10^{-2}	111.26	0.066	170.6	0.015	127.95	0.041
2.9×10^{-2}	105.02	0.076	161.29	0.017	125.44	0.044

increases to 8% if sinc3, whose length is 396.00 ms, is used. If longitudinal relaxation times of 1000 and 200 ms are assumed, the deviation increases to 3 and 14% for rectangular pulse and to 16 and 57% for sinc3.

Soliton FWHM bandwidth has been calculated to be 9 Hz for $T_2 = \infty$ and 24 Hz for $T_2 = 20$ ms. The shortening and filtering of the solitons induce no bandwidth variations both for $T_2 = \infty$ and $T_2 = 20$ ms. If $T_2 = \infty$ is assumed, all the other pulses induce a maximum bandwidth reduction of about 9%. The reduction is of about 7%, if $T_2 = 20$ ms is assumed.

DISCUSSION

Rourke and Bush (*12*) give the definition of T_2-selective pulses. A T_2-selective pulse suppresses both longitudinal and transverse magnetization from structures with a specified T_2 value, inverting the magnetization from structures characterized by very large T_2 values and leaving unaffected very small T_2 species.

Once the T_2 value has been specified, it is simple to calculate the soliton pulse waveform by means of the equation given in (*12*). The main problem of soliton pulses is that to suppress signal from structures with T_2 values of tens of milliseconds, their lengths have to be in the order of several hundreds of milliseconds. Besides, such long pulses have very narrow frequency profiles.

In this paper, we address the problem of improving the applicability of T_2-selective pulses by finding shorter pulses which null the longitudinal magnetization of a specific T_2 species, but that leave some residual transverse magnetization.

In this paper, a specific T_2 value has been chosen ($T_{2\_ref} = 20$ ms) but the results can be assumed to be valid for any other values. In fact, it is enough to change the pulse length from L to $L_{act} = L(T_{2\_act}/T_{2\_ref})$.

The main result of this study is that a linear relationship between the natural logarithm of the residual transverse magnetization and the pulse length has been found for different pulse shapes. The longer the pulse, the smaller the amount of residual transverse magnetization, independent of the pulse type.

Once the longitudinal magnetization has been nulled and the accepted amount of transverse magnetization has been fixed, the described linear relation permits us to choose the most appropriate pulse to select structures with a given T_2 time. This result was already proved for shortened and filtered solitons (*14*).

The frequency bandwidth of a long pulse is very small and this represents an impediment to their application. We have found that all of the T_2-selective pulses analyzed in this paper have very similar bandwidths. Therefore, shortening pulses cannot be considered for the purpose of broadening frequency bandwidth.

In order to make long pulses less sensitive to main field inhomogeneities, Sussman *et al.* (*2*) suggest a solution which consists of interspersing the long-T_2 suppression pulse with 180° refocusing pulses at regular intervals. In principle, this technique can be used to broaden the bandwidth of long T_2-selective pulses too, even if it reduces the contrast due to T_1 effects.

The limited bandwidth is not a problem if T_2-selective pulses are used with very short specific T_2 values, e.g., for applications in MT imaging. To select T_2 species in the order of hundreds of microseconds, much shorter pulses must be

TABLE 3
Sinc Pulses T_2 Selective for Samples with $T_2 = 20$ ms

	Without filter		Hanning filter		Offset subtraction	
Pulse	Length (ms)	M_{xy}	Length (ms)	M_{xy}	Length (ms)	M_{xy}
sinc3	396.00	6.5×10^{-5}	296.88	5.9×10^{-4}	394.73	6.7×10^{-5}
sinc1	124.38	0.045	174.70	0.013	124.89	0.044

generated. To select structures characterized by a T_2 value of 200 μs, for example, a pulse length of 2.76 ms for a soliton pulse and of 0.85 ms for a rectangular pulse is required.

The soliton pulse selective for $T_2 = 200$ μs has a FWHM bandwidth of about 900 Hz for structures with long T_2 and of about 2.4 kHz for structures with $T_2 = 20$ ms. Approximately, soliton and rectangular pulses have the same bandwidth.

In MT imaging, suppression of short T_2 components is usually performed either by means of long RF pulses or by a series of brief RF pulses. The final result in both cases is reduced longitudinal magnetization for short T_2 species (*3, 4*). T_2-selective pulses could be an interesting alternative to these two MT techniques.

The T_2 selectivity, that is the relationships between longitudinal magnetization and T_2 values, has been compared for all pulses. All positive pulses, even the not shaped rectangular pulse and the sinc pulse with only the central lobe, have been found to have the same T_2 selectivity.

Sinc pulses with negative sidelobes have a different T_2 selectivity, especially for T_2 values larger than the reference T_2 value. In any case, it changes according to the number of sidelobes. If there is an even number of positive and negative sidelobes, the relaxation effects related to negative sidelobes are compensated by those due to positive sidelobes.

T_2-selective pulses can be used in applications were tissues with short T_2 values are examined (see Gold *et al.* (*1*)). In successive measurements with T_2-selective pulses having different specific T_2 values, structures with these T_2 relaxation times can be selectively excluded from a signal contribution to the image.

The property of nulling the longitudinal magnetization and the transverse magnetization allows the use of T_2-selective pulses as optimized saturation pulses without the necessity of following spoiling gradients to reduce the influence of arisen transverse magnetization.

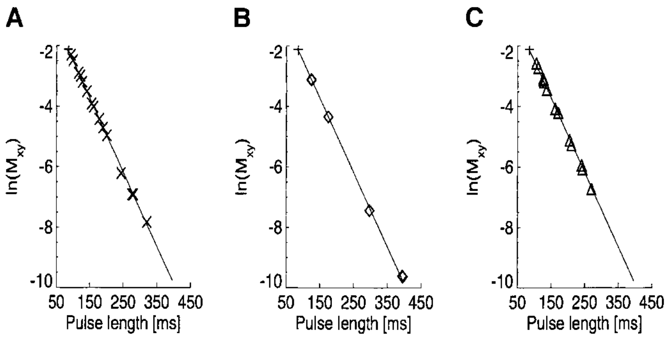

FIG. 4. Natural logarithm of the transverse magnetization as a function of the pulse length. In each case, the regression line has been calculated using the whole data set (data relative to the rectangular pulse and to the solitons, sinc, and gaussian pulses). (A) Rectangular (+) and soliton pulses (×); (B) rectangular (+) and sinc pulses (◇); (C) rectangular (+) and gaussian pulses (△).

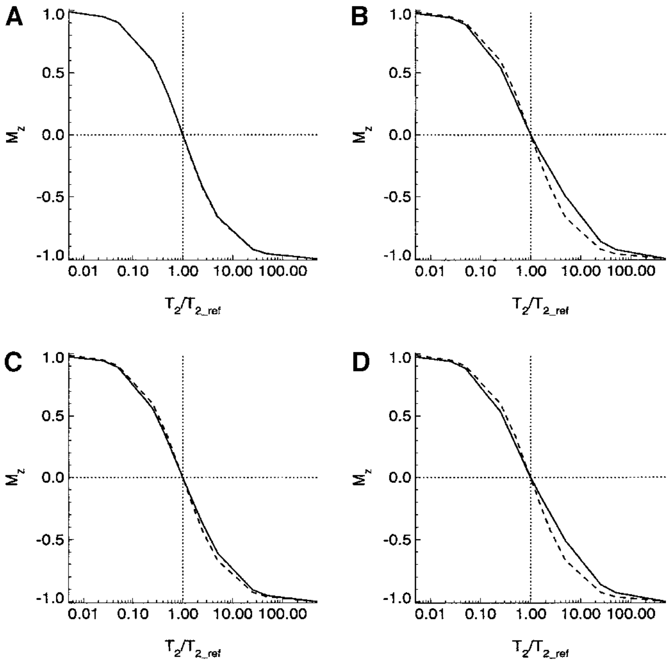

FIG. 5. Comparison between the T_2 selectivity of a nonfiltered soliton pulse calculated with an accuracy of 10^{-4} (dashed line) and that of the sinc pulses (solid line). (A) sinc1; (B) sinc3; (C) sinc5; (D) sinc7.

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