Novel Design for Notched RF Saturation Pulses using the SLR Transform

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Introduction

Saturation pulses are used to destroy the longitudinal magnetization to suppress sources of contamination or, in this case, to increase the contrast between long and short T1 components. Notched saturation pulses have been demonstrated in myocardial perfusion imaging [1] as a means to allow magnetization in certain regions (in the notch) to recover while simultaneously saturating surrounding regions. In [1], this was achieved by cosine modulating a conventional, selective saturation pulse to achieve two saturation bands with an unsaturated notch in between. The disadvantage of this approach is that increasing the width of the saturated region requires increasing RF amplitude and heating. In this abstract, we investigate the use of a hard, non-selective pulse to accomplish saturation over a wide spatial region, as well as a selective tip-up portion to return magnetization in the notch to the longitudinal axis.

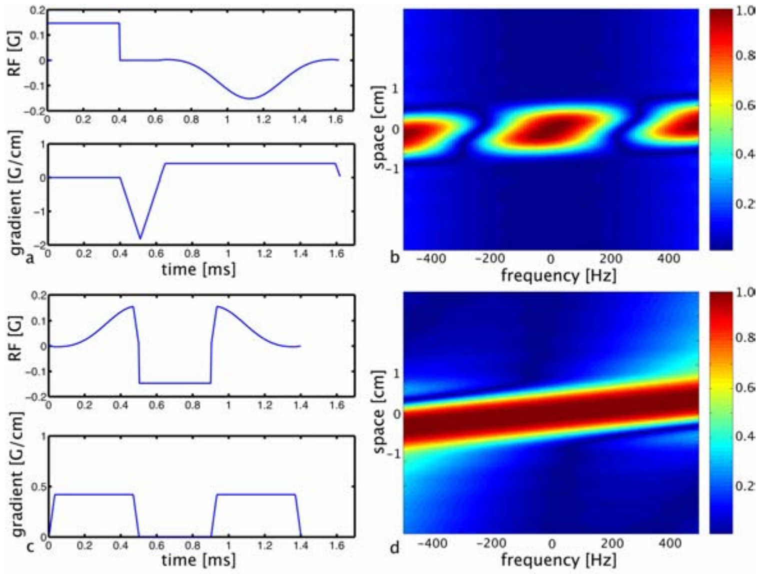

Figure 1: The frequency sensitivity of notched hard pulses. (a) The simple design consisting of a hard pulse followed by a selective tip-up is sensitive to off-resonance (b) because the two components are separated in time. (b) The residual longitudinal magnetization after the pulse in (a). (c) By transmitting the hard pulse between the two halves of the selective pulse, the nulls in the frequency profile are removed (d). The difference in tilt between (b) and (d) is discussed in the text.

Theory

The simplest design of a notched hard pulse is shown in Fig. 1(a), with a hard pulse followed by a selective tip-up pulse. The negative gradient lobe before the tip-up RF pulse serves to place the center of the selective portion at the same point in excitation k-space [?] as the hard pulse. The problem with this type of design is its sensitivity to off-resonance due to the separation in time between the hard pulse and the selective portion, seen as the periodic nulls in Fig. 1(b).
This off-resonance sensitivity can be mitigated with the "sandwich" design shown in Fig. 1(c): half of the selective pulse is played in the presence of a gradient, then the gradient is ramped to zero and the hard pulse is played, followed by the other half of the selective pulse. Since the two pulses are almost coincident in time, the periodic nulls seen in Fig. 1(b) are removed in (d). Interestingly, the tilt in the spectral-spatial profile, which will manifest as chemical-shift mis-registration in practice, is somewhat worse in Fig. 1(d) due to the selective portion of the pulse being played over a slightly longer duration.

The sharpness of the profile that can be achieved with the sandwich design is limited by the non-linearities of the Bloch equations (e.g. Fig. 2(d)). The method described below can be used to correct for this effect yielding highly selective, wide bandwidth notched pulses.

Methods and Results

The following design method was implemented in MATLAB, and is illustrated in Fig. 2(a). First, a filter corresponding to the Fourier transform of the desired longitudinal magnetization profile is computed using the Parks-McClellan algorithm. This waveform is scaled so that the sum of all the coefficients equals sin(alpha/2) where alpha is 90-degrees in this case. Then, sin(alpha/2) is subtracted from the central sample (this is not shown to scale in the diagram because this sample has relatively large amplitude). The inverse Shinnar-Le Roux (SLR) transform [2] is applied, slightly changing the shape of the waveform. The central, 90-degree sample is then removed and the two halves are corrected for the shape of the gradient waveform using the VERSE algorithm [3]. Lastly, a hard 90-degree pulse is placed between the two selective portions to give the pulse shown in Fig. 2(b).

Conclusions

The "sandwich" design for notched RF saturation pulses was introduced as a means to achieve saturation over a large spatial extent with insensitivity to off-resonance effects. The distortion of the spatial profile due to the non-linearity of the Bloch equations was solved with a novel use of the SLR transform that corrects the selective part of the pulse for the effect of the hard pulse at the center. The design method resulted in short, highly selective notched saturation pulses that are currently being evaluated for first-pass perfusion imaging in the heart [4].

References [1] G. S. Slavin et al. Radiology 219: 258-263 (2001) [2] J. M. Pauly et al. IEEE TMI 10:53-65 (1991) [3] Conolly et al. JMR 78:440-458 (1988) [4] T. Shin et al. ISMRM 2007

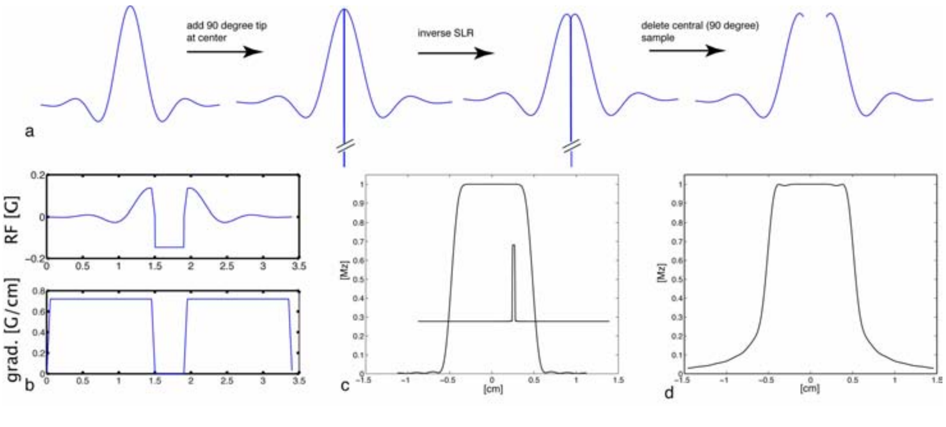

Figure 2: (a) Graphical representation of the design process described in the text. The designed filter is adjusted by adding a single sample corresponding to a 90-degree tip at the center. The inverse SLR transform is then applied, and this central sample is removed to yield the two halves of the selective portion of the pulse. (b) The resulting RF pulse and gradient waveform. The time-bandwidth product for the selective portion is 8. Note the short 3.4ms duration. (c) The longitudinal magnetization after application of the pulse showing excellent selectivity. The inset shows the wide spatial extent of the saturation. (d) The longitudinal magnetization profile that results by designing the selective portion with the SLR without the correction introduced here.