Broadband refocusing pulses with B_1 robustness and energy constraints

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Introduction

Broadband refocusing pulses are of great interest in localized spectroscopy for improving spatial selectivity, reducing chemical-shift displacements, and reducing anomalous J modulation. In practice the bandwidth of amplitude modulated pulses is limited by the maximum B_1 amplitude produced by the RF coil. Broad bandwidth is achieved by amplitude and phase modulated pulses designed with the Shinnar-Le Roux algorithm (SLR) [1], optimal control theory (OCT) [2], or with adiabatic pulses [3]. This work extends the OCT approach to limiting pulse energy, which can be necessary under constraints of specific absorption rate (SAR). **S**lice-selective **B**roadband **U**niversal rotation **B**y **O**ptimized **P**ulses (S-BUBOP) are compared to broadband SLR pulses (BB-SLR) and verified experimentally in the PRESS sequence.

Methods

RF pulses are optimized with a gradient ascent algorithm [4]. The quality function drives the RF pulse to $180°_x$ universal rotation of spins in the pass-band and prevention of excitation in the stop-band [2]. Immunity against B_1 variation is obtained by optimizing for a range of discrete B_1 offset values [5]. The cases of exact B_1 calibration (S-BUBOP-0%), and deviations $\pm 10\%$ (S-BUBOP-10%) and $\pm 20\%$ (S-BUBOP-20%) are considered. The pulse is optimized under two limitations: at each iteration of the algorithm, the pulse is truncated at the amplitude limit B_{1max} and scaled to $B_1(n) \longrightarrow B_1(n)\cdot\sqrt{E_{max}/E}$, if it exceeds the energy limit ($E>E_{max}$) [6]. Pulse energy is calculated according to $E \sim T/N \sum_{n=1}^{N} |B_1(n)|^2$, with T being pulse duration.

Exemplary pulses with the following specifications are optimized: time-bandwidth product $T{\cdot}BW=17.4$, fractional transition width $FTW=0.18$, ratio of pulse bandwidth to peak B_1 amplitude $BW/B_{1max}=2.95$. For a scaling of $B_{1max}=23\mu T$ ($1kHz$ for ^{1}H), these pulses have $BW=2950Hz$ and $T=5.9ms$. These specifications correspond to the BB-SLR pulse with $nbw=110$ from [1], with the exception of $180°$ rotation instead of $172°$. Pulse energies are given relative to a conventional, amplitude modulated SLR pulse with $T{\cdot}BW=4$, $FTW=0.43$, $BW/B_{1max}=0.95$. PRESS experiments on a phantom with oil and water are performed on a 3T GE Signa HDx using a head T/R coil.

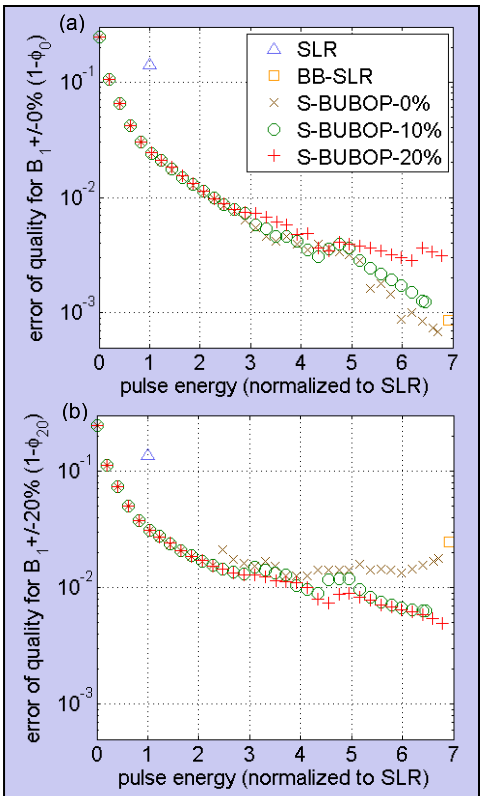

Fig. 1: Error of pulse quality depending on pulse energy for the exemplary pulses. In (a) the quality considers only $B_1=1$, while in (b) the quality takes into account miscalibrations of $B_1\pm 20\%$.

Results and Discussion

Optimizations are performed for different energy limits, while keeping T, BW, FTW, and B_{1max} fixed. This gives a curve of pulse quality for different pulse energies. Error of quality is plotted against pulse energy, using the quality function for exact B_1 calibration (Fig. 1a) and with B_1 miscalibration of $\pm 20\%$ (Fig. 1b). The standard SLR pulse with the same B_{1max} is given for comparison. Its quality is low because it is not broadband.

The quality increases with larger pulse energy. Pulses optimized without considering B_1 deviations (S-BUBOP-0%) reach a slightly better quality with slightly less energy compared to BB-SLR (see cross and square in Fig. 1a). For the same energy, pulses optimized with robustness against B_1 inhomogeneity perform worse for exact B_1 calibration (see circle and plus sign in Fig. 1a), compared to S-BUBOP-0%. For the same quality, pulses with better B_1 robustness need more energy.

When looking at pulse performance under $B_1\pm 20\%$ the BB-SLR pulse and S-BUBOP-0% pulses perform worse (see cross and square in Fig. 1b). Optimizing for $B_1\pm 10\%$ gives good robustness against $B_1\pm 20\%$. For $B_1\pm 20\%$ the best pulse quality of 0.995 is reached with relative pulse energy of 6.8.

In a PRESS experiment the S-BUBOP-20% pulse with energy 4.5 is compared to SLR and BB-SLR (Fig. 2). The chemical-shift displacement between oil and water resonances is reduced with S-BUBOP-20% and BB-SLR (Fig. 2g). With a B_1 miscalibration of 20% the BB-SLR shows signal loss, while S-BUBOP-20% performs well (Fig. 2h).

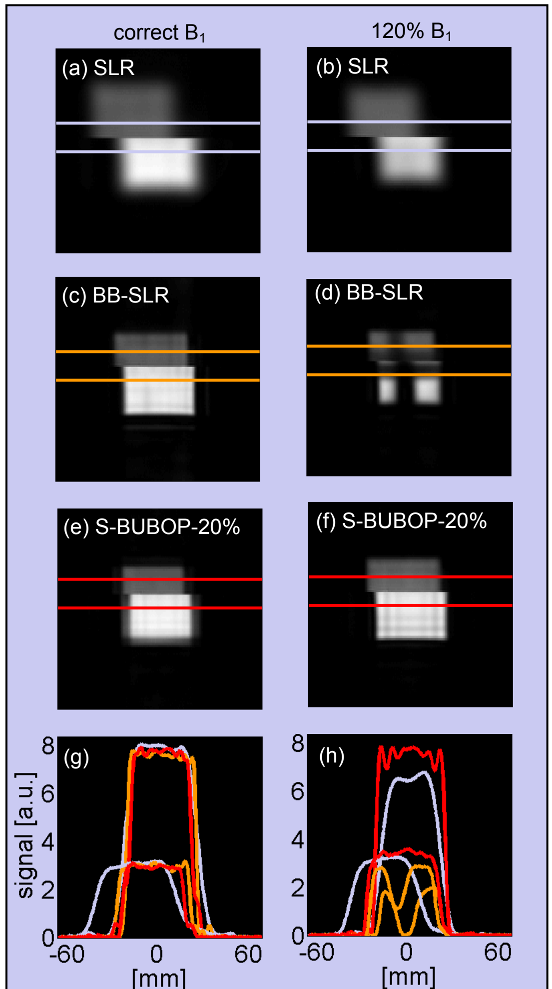

Fig. 2: (a-f) PRESS CSI on oil-water phantom. (g,h) Image profiles through oil and water regions from each of the images above. In the left column the B_1 amplitude was calibrated correctly, while in the right column B_1 was increased by 20%.

Conclusions

Broadband pulses generally require more energy than non-broadband pulses. Compared to a standard SLR pulse, the exemplary S-BUBOP-20% pulse increases the bandwidth by a factor of 3 using a factor of 4.5 larger pulse energy, and with a smaller transition zone. Unlike BB-SLR pulses, S-BUBOP are robust against B_1 miscalibrations.

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References: [1] Schulte RF et al. JMR 190:271 (2008); [2] Janich et al. ISMRM 2860 (2010); [3] Garwood et al. JMR 153:155 (2001); [4] Khaneja N et al. JMR 172:296 (2005); [5] Kobzar K et al. JMR 173:229 (2005); [6] Kobzar K et al. JMR 194:58 (2008)