Tailored Sinc Pulses for Uniform Excitation in RF EPR Imaging

N. Devasahayam[1], R. Murugesan[1], K-I. Matsumoto[1], J. B. Mitchell[1], J. A. Cook[1], S. Subramanian[1], M. K. Cherukuri[1]

[1]Radiation Biology Branch, NCI/NIH, Bethesda, MD, United States

Synopsis

In time-domain EPR imaging, the large bandwidths of 10-12 MHz required for imaging a mouse even under nominal gradients of about 1G/cm, makes uniform excitation rather challenging, because of the sinc [sin(x)/x] profile of the power spectrum of a rectangular pulse. This situation is further compounded by the 'Guassian droop' in the resonator response dictated by the quality factor. The use of tailored sinc shaped pulses with nanosecond time resolution with a single side lobe with optimally enhanced amplitude compensates for both the factors, leading to quantitative intensity information, necessary for evaluating in vivo pO_2.

In time domain RF EPR, one uses rectangular pulses of ~100 ns duration to excite the spin system, and the resulting FIDs after FT can be treated in the same way as in CW for image reconstruction using filtered back projection. However, the very short T_2* of the spin probes under imaging gradients leads to artifacts, especially in images of oblong objects. We employ an alternative method of collecting data using pure phase encoding of a single point in the FID, after a short delay 'τ' following the pulse, using the so-called Single Point or Constant Time modality (SPI or CTI) which leads to images that are least affected by the line width. Besides, the dead-time resulting from finite resonator quality factor Q, and the receiver recovery time leads intensity artifacts in the time-domain images. SPI gives good images without any spectral influence. It is possible to recover the spectral information by following pixel-wise intensity as a function of the delay 'τ'. Uniform excitation throughout the frequency bandwidth corresponding to the field of view should make the recovery of spatial and spectral information more reliable in imaging experiments. In this note we present a method to generate shaped radio frequency pulses for uniform excitation of electron spins in time-domain RF EPR imaging

Materials and methods

Since the FT of a rectangular RF pulse leads to a sinc profile for the power spectrum, an RF pulse with a sinc profile should give a uniform ('top-hat' shape) power profiles. An ideal sinc pulse will be too long, and therefore in practice, one uses a truncated sinc pulse with one or two lobes on either side. In time domain EPR we are constrained to limit the sinc pulse to just a single side lobe. This will lead to fairly uniform excitation over a bandwidth $1/t_p$, where t_p is the width of the central lobe of the sinc pulse. However, in RF EPR, because of the effect of the resonator Q, which leads to rapid attenuation of power away from the carrier frequency, we have to further accentuate the power profiles at either extreme. This can be achieved, for a sinc pulse with a single side lobe, by changing the relative amplitudes of the central lobe to that of the side lobe. Reducing the relative magnitude of the side lobes leads to an enhancement of power density at the carrier frequency, while accentuating the side lobes leads to a 'concave' power profile with the central power density reduced in exchange for an enhanced power density at the extremes. Fig. 1 summarizes the above concept.

A commercial waveform generator, ANALOGIC DBS 2050A (Analogic Corporation, Peabody, MA) was selected based on its sampling rate (2.4 GS/s, single channel) as well as its capability to generate precise standard waveforms (square, sine, positive and negative ramps, sinc, etc.). Very short rise/fall times of the pulses (400 ps), good vertical resolution (8 bits) and high programmable gain (60 dB) and offset are other added advantages provided by the ANALOGIC DBS 2050A. The pulse shaping unit is integrated with the transmit arm of our pulsed RF FT EPR imager. By suitably tailoring the sinc pulse we were able to compensate for the Q profile of the resonator, and generate images with intensity profiles that can provide quantitative information for oximetry.

Results & Discussion

The results of applying the shaped sinc pulses on the power spectrum in an actual experimental situation are depicted in Fig. 2. It can be seen that a sinc pulse with the side lobe intensities appropriately enhanced relative to the central lobe can in fact compensate for the Q-profile of the resonator. This is further confirmed by experiments on a 5-tube phantom, where the tailored pulse shows more uniform excitation compared to the rectangular pulse (Fig.3). We have also evaluated the use of tailored sinc pulse for *in vivo* applications. Fig. 4 shows 2D images of a C3H mouse infused with 75 μL of 100 mM Oxo63 solution obtained with a 90° rectangular pulse (A), and a tailored sinc pulse that provides a uniform excitation with additional compensation for the Q-profile of the resonator (B). It can be seen that the rectangular pulse provides a relatively intense central region with a reduced intensity for the bladder and thoracic region, whereas the tailored pulse achieves a more uniform excitation bringing in extra details from the extreme regions of the field of view, compensating for the Q-profile of the resonator.

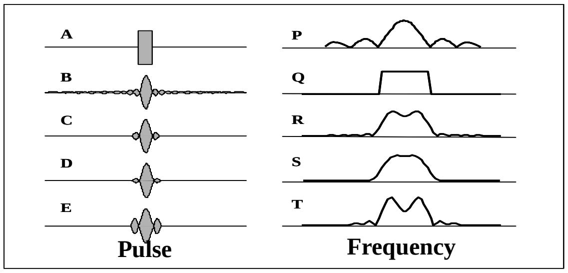

Fig.1 Fourier Relationship between pulse shape and the corresponding power spectrum. In the left column, a rectangular (A), an ideal sinc (B), truncated sinc with only one side lobe (C), side-lobe-attenuated sinc (D) and side-lobe-enhanced sinc (E) pulses are shown. In the right column, the corresponding power spectra close to the carrier frequency are shown. The rectangular pulse generates the sinc profile power spectrum (P) while the sinc pulse generates the ideal uniform excitation (Q). The truncated sinc pulse of width t_p shows more uniform excitation in the frequency region $\pm 1/2\, t_p$ centered about the carrier compared to the rectangular pulse, but it has a slight concave power profile at the center(R). This can be made more uniform by reducing the intensity of the side lobe relative to the central lobe (S). An enhancement of the side lobe intensity leads to an increase of spectral density at the extremes of the power profile with a concomitant reduction in the center (T), and thus can compensate for the coil Q-profile.

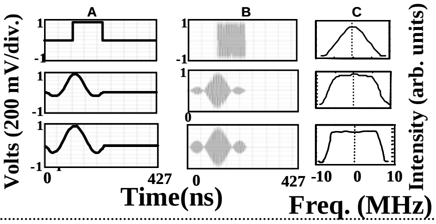

Fig.2 Pulse shape(A), modulated carrier (B), and the corresponding (measured) excitation profile (C) of the resonator for square pulse(I), sinc pulse (II) and tailored sinc pulse (III) for Q-compensation. The power profiles were mapped over a frequency offset of ±10 MHz.

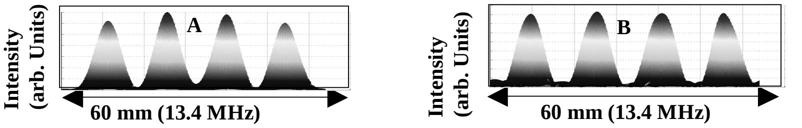

Fig.3 Mesh plots of 2D projection SPI images of the four-tube phantom (all the four tubes, 5mm i.d., contained equal spin count, 45 μL of 10 mM Oxo63) corresponding to the profile of the resonator power spectrum for (A) rectangular pulse: 110 ns. (B) Tailored sinc pulse, overall length 130 ns. The flattening of the power spectrum in going from rectangular to sinc profile and the equalization of intensities in the mesh plots can be clearly seen.

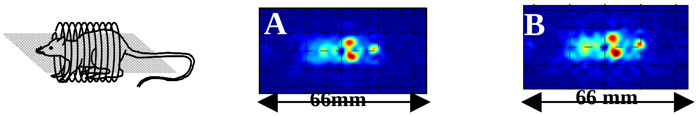

Fig.4 2D images of C3H mouse obtained using a 110 ns (A) rectangular and (B) modified sinc pulse in a 25 x 50 mm cylindrical resonator with a Q of 25. Images taken with a rectangular pulse show marked decrease in intensity at the periphery of the image. A cartoon of the mouse in the resonator coil and the image plane is shown on the left (not to scale).

References: [1] R. Freeman,, Progress in Nuclear Magnetic Resonance Spectroscopy, J. W. Emsley, J. Feeney andL. H. Sutcliffe (Series Eds.) Pergamon, Oxford, 1998. [2] D. E. Hyre,L. D. Spicer, J. Magn. Reson. 108 (1995) 12-21.