Imaging, Acquisition & Reconstruction

Gerald B. Matson **gerald.matson@ucsf.edu**

Highlights

- All MRI experiments use RF pulses for signal excitation
- A large number of RF pulse design methods are used for a variety of RF pulse types
- Some understanding of design methods and RF pulse types is essential for choosing appropriate design methods and RF pulse types
- This overview emphasizes concepts rather than focusing on mathematical details

Overview of RF Pulses Designs: From Basics to State-of-the-Art

- **Target Audience:** Persons interested in understanding how RF pulses perform, or are interested in RF pulse design methods, or in development of improved pulses for particular circumstances.
- **Objectives**: Overview of types of RF pulses used in MRI, and introduction of RF pulse design methods.
- **Purpose:** Provide insight into RF pulse design methods, and also show limitations of certain pulse types.
- **Results**: Primarily through the use of figures and animations, provide an understanding of RF pulse design methods for a variety of pulse types.
- **Discussion/Conclusion:** Depending on needs, a variety of RF pulse design methods are available. However, consideration of design methods and pulse limitations must be taken into account.

Introduction:

While 3D MRI experiments use non-selective RF pulses, all other MRI sequences make us of selective RF pulses. Even for 3D MRI experiments, considerations of specific absorption rate (SAR) and resonance offset need to be taken into account. A brief example of the use of non-selective (rectangular) pulses will be presented.

Obviously, the most common use of selective RF pulses is for slice selection. The nomenclature used for selective pulses is illustrated in Fig. 1, using an equal ripple pulse [1] as an example.

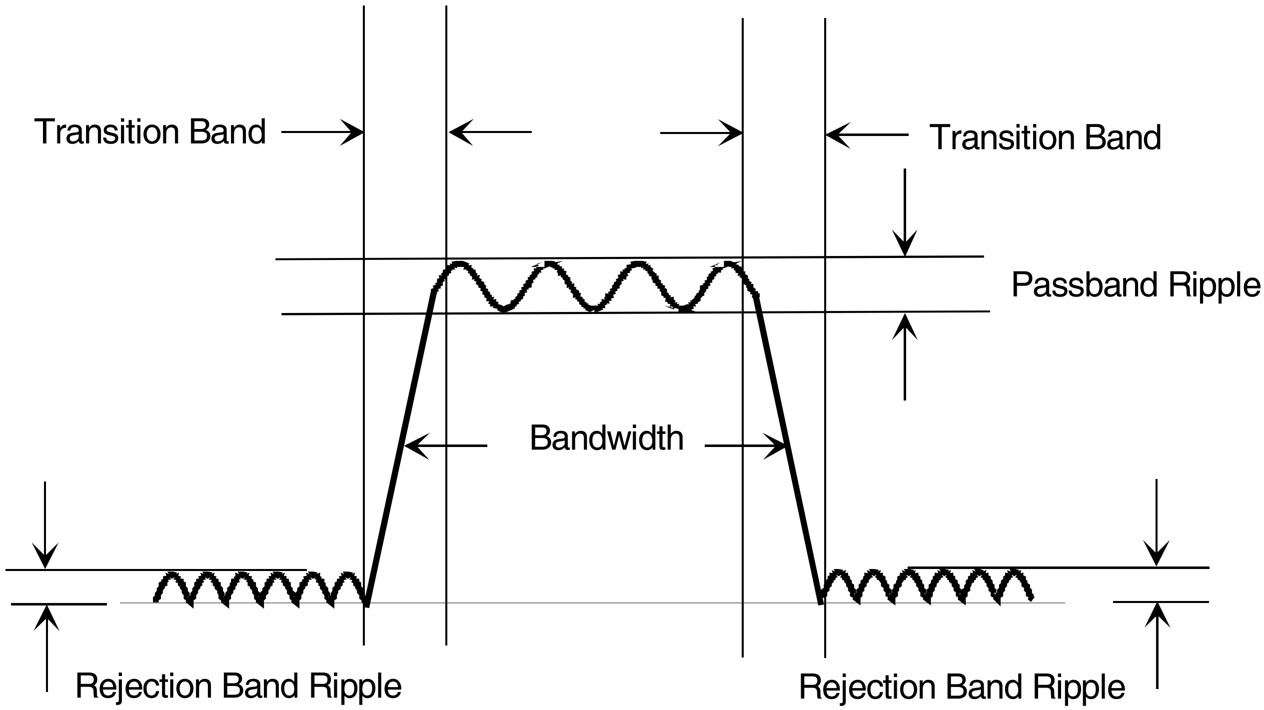

Figure 1. Illustration of the selective pulse nomenclature using an equal ripple pulse as an example.

Using what is known as the small-tip approximation [2] enables the slice profile to be expressed as the Fourier transform (FT) of the shape of the RF pulse. That is, an RF pulse (or more accurately, the rotating magnetic field produced by the pulse and designated as B_1) modulated by a sinc shape would be expected to produce a rectangular-shaped excitation profile. However, unlike the sinc function, the RF pulse cannot extend for forever, and the sinc shape is typically truncated by a Gaussian apodization function (sinc-Gauss pulse), leading to significant transition bands on the slice profile. Difficulties with sinc-Gauss pulses include the fact that the slice width narrows as the tip angle is increased, the slice profile degrades as the tip angle approaches 90 degrees, and the sinc- gauss pulses do not produce good spin echo pulses. Nevertheless, sinc-Gauss RF pulses remain in widespread use today. Animations will be presented showing the operation of frequency selective pulses.

Frequency-Selective RF pulse optimization:

In efforts to improve on sinc-Gauss pulses, optimization methods, including optimal control methods, were used by Conolly et al. [3] , Murdoch et al. [4], and Mao et al. [5], who showed they were able to generate improved large tip angle pulses, including excellent spin echo pulses. Murdoch et al. also optimized inversion pulses for immunity to B_1 inhomogeneity. The disadvantages of these approaches were: 1) Different optimization parameters had to be adjusted experimentally to achieve desired results, 2) the optimizations took time, and 3) there was no certainty that a global optimal solution had been obtained.

A major step forward in optimization of selective RF pulses was taken with the Pauly et al. presentation of the Shinnar – Le Roux (SLR) pulse design [1], which made use of efficient filter design algorithms for the RF pulse optimization. Because of the importance of this design method, the concepts behind this optimization method will be outlined in the lecture. Not only was the optimization very rapid, but, equally important, the authors showed the filter parameters could by re-interpreted to apply to the RF pulse design, so that the excitation parameters (transition bandwidth, bandpass ripple, and rejection band ripple) were known prior to the pulse optimization. Thus, the trial and error approach of adjusting parameters to achieve a desired pulse, inherent in the earlier optimization methods, was eliminated. While multiple filter optimization methods were available, the authors suggested the Parks-McClellan algorithm be used, which produced equal ripple pulses as shown in Fig. 1. Finally, the authors proved that, for linear phase pulses (in which the magnetization could be coalesced by a gradient refocusing pulse) the SLR design produced i) the shortest pulse, in that a shorter pulse with equal transition bands and equal passband and rejection band ripples was not possible, as well as ii) the lowest SAR pulse. While the excitation and spin echo pulses were designed as linear phase pulses, the authors showed maximum or minimum phase pulses were more efficient for saturation or inversion purposes. Examples of these pulses, produced with Matpulse [6], will be presented.

Despite the advantages of the SLR design, some limitations remained. The SLR design required higher RF amplitudes for larger bandwidth pulses (particularly a problem for spin echo pulses, in which the peak voltage is approximately four times that of an equivalent 90 degree pulse), and (as will be shown in the lecture) the slice profile is degraded in the case of B_1 inhomogeneity.

Pulses with immunity to B1 inhomogeneity:

Adiabatic Pulses:

Particularly in the early days of MRI, coils that did not produce homogeneous B1 fields were in use, and there was interest in RF pulses with immunity to B1 inhomogeneity. Both the Pines group [7] and Hoult's group [8] showed that a hyperbolic-shaped RF pulse (hyperbolic secant) could be used for slice-selective inversion, and that the inversion profile remained virtually unchanged with RF power once a minimum threshold had been exceeded. Despite the fact the adiabatic inversion pulses are SAR intensive, because of their robustness, they are often used for inversion pulses in MRI experiments requiring accurate magnetization inversion.

It is useful to consider the hyperbolic secant pulse as belonging to a family of adiabatic pulses, all with slightly different modulation functions, depending on their application (broadband, non-selective inversion, or frequency-selective inversion). A large number of investigators have contributed to various modulations for these pulses, with the uniting characteristic of these pulses being that the orientation of the B_1 field with any magnetization isochromat being inverted does not change significantly during the pulse.

Finally, adiabatic pulses can be used for more than inversion. Dual adiabatic pulses can be used to generate a spin echo [9], where the phase modulation of the echo produced by the first pulse is undone by the second. Additionally, as illustrated by Garwood and Ke [10], adiabatic segments can be joined to produce a variety of specialized pulsed. However, the only pulse shown capable of multislice excitation in an MRI experiment is the BIR-4 [10], which has proven to be too long and SAR intensive for general usage in MRI experiments. Animations of adiabatic inversion, and the operation of the BIR-4 pulse, will be provided to illustrate the concept of adiabatic pulses.

Non-Adiabatic Pulses:

While the strength of adiabatic pulses is that they can achieve their designed tip over a large range of B_1 inhomogeneity, their weakness is the high power and long length required, generating high SAR and becoming susceptible to relaxation and magnetization transfer effects during the pulse. At high field, where the B_1 field is inherently inhomogeneous over human tissue [11], the design of efficient excitation pulses with immunity to B1 inhomogeneity has proved difficult, although the multicoil excitation methods discussed at the end of this lecture do hold considerable promise. For 3D experiments, where frequency selection is not needed, Boulant et al. [12, 13], Moore et al. [14], and Hui and Matson [15] independently developed somewhat analogous excitation pulses with some immunity to B1 inhomogeneity and resonance offset. However, the pulses do so at the expense of much larger SAR than their rectangular counterparts [15], and are susceptible to relaxation [16] and magnetization transfer (MT) effects [17]. The Matpulse menu for the Hui and Matson pulses is shown in Fig. 2, which indicates how parameters may be selected, and also indicates that the method also allows for inversion pulses, which, by operating over a more limited range of B_1 inhomogeneity and resonance offset than hyperbolic secant designs, can be more efficient than hyperbolic secant designs.

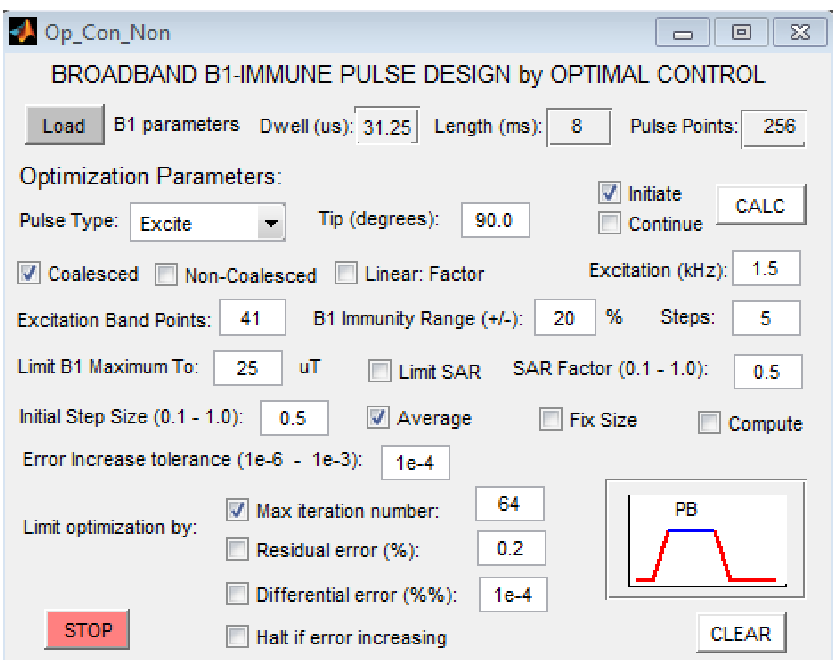

Figure 2. Matpulse menu for Hui and Liu B_1-immune non-selective pulses.

Alleviating the Disadvantages of SLR Designs:

Lowering the maximum RF voltage:

Near the beginning of the lecture we mentioned the high RF voltage required for the SLR spin echo pulse. Conolly et al. [18] offer a remedy by reducing the gradient amplitude during the high amplitude region of the pulse, allowing the amplitude to be reduced, although the length is increased. However, the method (variable rate selective excitation, or VERSE) is actually highly flexible, and enables the pulse to be shortened if the gradient is not already near maximum and can be increased during the low amplitude region of the pulse [19, 20]. Other analogous methods, such as FOCI pulses [20], can be thought of as versions of VERSE. However, care must be taken when resonance offsets are present, as the method makes the profile more sensitive to degradation with resonance offset. Examples using the Matpulse version of VERSE, termed remapping, will be presented to illustrate the method.

Increasing the Bandwidth:

In the SLR design, increasing the bandwidth is accomplished by increasing the RF amplitude, which in turn is limited by the MRI instrument (typically to around 20 μT). While this limitation is more typically a problem for spectroscopy, it can also be limiting for slab selection where a strong selection gradient is desired. Although they were designing RF pulses for spectroscopy, Matson et al. [21] showed that submitting the SLR pulse to an optimization control routine (available in Matpulse) enabled the excitation bandwidth to be broadened without increasing the RF amplitude, albeit at the expense of lengthening of the pulse.

Providing Immunity to B1 Inhomogeneity:

Early examples of cascades of rectangular (non-selective) excitation pulses providing some immunity to B_1 inhomogeneity were provided by Levitt [22]. As SLR pulses, preceded by a de-phasing gradient and followed by a rephrasing gradient, can be cascaded just as rectangular pulses, the process established by Levitt can be accomplished with frequency-selective pulses. Reversing the sign of the gradient in succeeding pulses produces a more efficient cascade. Cascades with immunity to B_1 inhomogeneity have been presented by several authors [23-25]. However, due to the long length and high SAR produced by these pulses, it is not yet clear if they have practical value for MRI experiments with humans.

The development of low power, high bandwidth spin echo pulses with B_1 immunity have proven to be particularly problematic [26]. Recently, Balchandani et al. [27] have shown that the SLR design can be re-formulated to produce adiabatic (quadrature phase) pulses, and the authors have leveraged this to produce a matched excitation – spin echo pulse pair for generation of spin echoes with a B_1 insensitive RF pulses. However, even this clever design is both long (15 ms) and SAR intensive.

Multidimensional Pulses Transmitted with Multiple Coils:

The Idea of Multidimensional Excitation:

Developing RF pulses that provide uniform tipping at high field, where the B_1 field is inherently inhomogeneous, is a rapidly developing field, with a large number of contributions over the last few years, and only a brief introduction is provided here. As the SAR increases with frequency, development of suitable RF pulses, while staying within acceptable SAR ranges, has made this field particularly challenging. However, the combination of multidimensional RF pulses, combined with the use of multiple transmit coils, does hold promise.

The ideas of multidimensional excitation were assisted by a pair of papers from the Macovski group [28, 29], in which it was demonstrated that, somewhat analogous to the idea of image formation by Fourier transform (FT) of the signal acquired over the acquisition k-space, the RF pulses required for multidimensional excitation could be presented as the Fourier transform of the desired (and properly weighted) excitation pattern over the excitation k-space. It is important to note that the excitation k-space is defined differently than the acquisition k-space used in MRI. A simple example will be presented to illustrate the concept of multidimensional excitation.

While early ideas of multidimensional excitation showed that, indeed, distinct patterns could be excited by the Pauly et al. formalism [28, 29], any distinct pattern (with sharp edges) required fine sampling of the excitation k-space, which resulted in long duration RF pulses. However, it turns out that the pulse length can be alleviated through the use of multiple transmit coils.

The Idea of Using Multiple Excitation Coils:
Broadly speaking, the use of multiple receive coils provides somewhat redundant information. In principle, it should be possible to leverage this additional information into improved resolution, or less time spent in acquisition [30]. In SMASH [31] and GRAPPA [32] , the acquisition is speeded up by undersampling k-space, and approximating the missing k-space points through knowledge of the sensitivity of the receive coils and appropriate combinations of acquired k-space points, while in SENSE [33], only a small field of view is acquired, and the full image recovered from the resulting aliased image through knowledge of the sensitivity profiles of the receive coils.

In an analogous manner, it is possible to shorten the length of a multidimensional RF pulse through the use of multiple transmit coils. However, in much the same way that the efficiencies of GRAPPA and SENSE depend upon the orientation, geometry, and sensitivity profiles of the receive coils, the ability to shorten a multidimensional RF pulse depends on the orientation, geometry, and transmit profiles of the multiple transmit coils [34, 35]. One saving grace is that the B_1 field does not change drastically over tissue such as the human head, so the excitation k-space sampling can be rather coarse. These pulses have been variously named as spokes pulses [36], fast-kz pulses [37], or Kτ –points pulses [38], to indicate they are designed as multicoil, sparse excitation k-space RF pulses.

Due to the large number of contributions in this rapidly developing field, in this brief overview we point to just a couple of recent, representative examples.

Cloos et al. [39] have demonstrated MP RAGE experiments with their non-slice-selective Kτ-points pulses on human heads with an eight channel array, using a minimal of k-space locations for the excitation, and including transit sensitivity maps and resonance offsets (B_0 maps) in the design of the pulses. The pulse scheme calculation used what is termed the spatial domain method [40], and incorporated a magnitude least squares optimization procedure [36]. The MP RAGE experiments included inversion pulses designed similarly to the excitation pulses but with reduced SAR compared to adiabatic inversion pulses. This same group has also shown promising results for non-selective spin echo pulses [41], again using a minimal of k-space locations for the excitation, and an optimal control method for optimization.

Zheng et al. [42] have used slice selective pulses to present improved EPI results at 7T over human heads through use of an eight channel array transmit / receive coil, and a 2D excitation k-space sampling of 5 points. The pulse design utilized B_0 maps of the head to design the pulses to compensate for the through slice-plane frequency spread to minimize susceptibility-induced signal losses that accompany more traditional slice-selective pulses at high field. The RF pulse design used the spatial domain design method [40], with a separately designed pulse for each of the seven slices. Thus, the design also required prior B_0 maps and measures of the transmit profiles for each of the coils for design of the RF pulses [42].

While the drawback for the use of these styles of pulses is the time required for measurements of B_0 maps and coil transmit profiles, which vary from person to person, in addition to the compute time to design the RF pulses, the promise of improved MRI results at high filed continues to spur advancements in this exciting, albeit complicated, field.

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