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Simple Method for RF Pulse Measurement using Gradient Reversal

Vanessa Landes^{1,*} and Krishna Nayak²

¹Department of Biomedical Engineering, Viterbi School of Engineering, University of Southern California, Los Angeles, California, USA

²Ming Hsieh Department of Electrical Engineering, Viterbi School of Engineering, University of Southern California, Los Angeles, California, USA

Abstract

Purpose—To develop and evaluate a simple method for measuring the envelope of small-tip RF excitation waveforms in MRI, without extra hardware or synchronization.

Theory and Methods—Gradient Reversal Approach to Evaluate RF (GRATER) involves RF excitation with a constant gradient and reversal of that gradient during signal reception to acquire the time-reversed version of an RF envelope. An outer-volume suppression (OVS) pre-pulse is optionally used to pre-select a uniform volume. GRATER was evaluated in phantom and in-vivo experiments. It was compared to the programmed waveform and the traditional pick-up coil method.

Results—In uniform phantom experiments, pick-up coil, GRATER, and OVS+GRATER matched the programmed waveforms to <2.1%, <6.1% and <2.4% normalized root mean square error (NRMSE), respectively, for real RF pulses with flip angle 30°, time-bandwidth product 2 to 8, and 2 to 5 excitation bands. For flip angles >30°, GRATER measurement error increased as predicted by Bloch simulation. Fat-water phantom and in-vivo experiments with OVS+GRATER demonstrated <6.4% NRMSE.

Conclusion—GRATER sequence measures small-tip RF envelopes without extra hardware or synchronization in just over two times the RF duration. GRATER may be useful in pre-scan calibration and for measurement and pre-compensation of RF amplifier nonlinearity.

Keywords

RF fidelity; RF nonlinearity; predistortion correction

INTRODUCTION

MRI pulse sequences depend on accurate production of RF waveforms for precise excitation. Pulses with a high peak transmit radiofrequency magnetic field (B₁⁺) and rapid

*Corresponding Author: Vanessa Landes, 3740 McClintock Ave, EEB 400, University of Southern California, Los Angeles, CA 90089-2564, Phone: (213) 572-7827, Fax: (213) 740-4651, vlandes@usc.edu.

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fluctuations in their RF supply current can push the RF power amplifier to its limits, causing amplifier nonlinearity and incidental phase modulation (1–3). This leads to an incorrectly transmitted RF envelope and imperfect frequency profile, which can lead to undesirable effects in several advanced MRI applications (4). For example, distortions of multi-band RF pulse envelopes can excite additional, unwanted side-lobes and introduce errors in the separated, desired slices (2,5). Second, distortions of RF pulses used in Hydrogen MR spectroscopy can lead to incorrect metabolite concentration quantification as distorted water suppression pulses saturate signal outside the expected bandwidth (6). Third, distortions of RF pulses used in hyperpolarized Xenon lung imaging can prevent excitation of Xenon inside vessels and tissues, and instead excite the 50-fold larger gas-phase magnetization pool (7). Due to increasing demand for higher fields, transmit array technology, and more complex excitation waveforms (8), accurate control of the RF field is now more necessary than ever.

Recent work has focused on improving the linearity of RF excitation by measuring the RF envelope to create a new waveform that corrects for expected nonlinearity. For example, Stang et al. (9,10) utilized a Vector Iterative Predistortion (VIP) method to iteratively detect and correct errors in RF transmit behavior in four parallel transmit channels until the detected RF converged to the expected RF. Several groups have utilized forms of Cartesian feedback (CF), namely frequency-offset CF, to linearize coil current in multi-coil transmit arrays through a negative feedback loop that corrects for transmit amplitude and phase error (8,11–13). Recently, Zhu et. al (2) presented a simple and elegant approach to correct for envelope distortion. This method uses an external pickup-coil placed in the scanner bore to measure RF and processes the acquired data offline to determine the actualized envelope in relation to the programmed envelope. This method requires less hardware and processing and has been demonstrated using single-channel transmit in a real RF pulse. The aforementioned methods can all minimize amplifier distortions, but at the cost of extra hardware, synchronization, and processing to measure actualized RF waveforms.

In this paper, we present a fast and simple method to measure RF waveforms without the need for extra hardware and synchronization. The proposed Gradient-Reversal Approach to Evaluate RF (GRATER) involves 1) excitation in the presence of a gradient and 2) immediate signal acquisition in the presence of an inverted gradient along the same axis. GRATER relies on the scanner's intrinsic hardware and software to obtain the RF envelope by filtering and demodulating the RF signal. We demonstrate in phantoms and in-vivo the ability of GRATER to quickly and easily capture RF waveforms and compare measurements to the “gold standard” pick-up coil (PUC) method (2).

THEORY

Figure 1 shows the GRATER pulse sequence for RF measurement with an optional outer volume suppression (OVS) pre-pulse (14). A constant gradient used during RF excitation is inverted during signal reception to acquire a time-reversed version of the RF pulse; the rationale follows.

RF Excitation with Constant Gradient

Assuming a uniform object along the axis of an applied gradient and the small tip-angle approximation, the transverse magnetization $M(\tau, r)$ can be described at time τ after the RF pulse is played to select slice z . Here, $M(\tau, r)$ is proportional to the phase accumulated over the duration of the gradient with amplitude G to select slice z (i.e., $\omega(G, r) = \gamma G z$), multiplied by the inverse Fourier transform of the angular frequency $\omega_1(s)$ at frequency $\omega(G, r)$ (see Equation 1):

$$M(\tau, r) \propto e^{-i\omega(G, r)\tau} \int_{s=0}^{\tau} e^{i\omega(G, r)s} \omega_1(s) ds \quad [1]$$

The angular frequency $\omega_1(s)$ is a function of the Larmor frequency γ and the RF pulse $B_1(s)$, i.e. $\omega_1(s) = \gamma B_1(s)$.

Signal Reception with Inverted Gradient

Using the small-tip approximation, GRATER signal is defined as $S_{GR}(t)$, where $t = 0$ corresponds to the beginning of the readout gradient with amplitude $-G$. Here, $S_{GR}(t)$ is proportional to the inverse Fourier transform of the Magnetization at the frequency which corresponds to phase accrual during the readout gradient $-\omega(G, r) = \gamma(-G)z$. Phase terms $\omega(r)$ and $R_2^*(r)$ are added to account for off-resonance and transverse relaxation rates, respectively (see Equation 2):

$$S_{GR}(t) \propto \int_x \int_y \int_z M(\tau, r) e^{-i(-\omega(G, r))t} e^{-i\Delta\omega(r)t} e^{-R_2^*(r)t} dz dy dx \quad [2]$$

Assuming the object is uniform in x and y , off-resonance is minimal ($\omega(r) \approx 0$), and R_2^* effects are minimal ($R_2^*(r) \approx 0$), Equation 2 can be simplified:

$$S_{GR}(t) \propto \int_z M(\tau, r) e^{-i(-\omega(G, r))t} dz \quad [3]$$

The GRATER Signal

Inserting Equation 1 into Equation 3, terms can be grouped such that the GRATER signal is proportional to the integral of the RF pulse with respect to s , multiplied by integrals of exponential terms with respect to s and z . These exponential terms can be regrouped and Fourier transformed with respect to z to obtain a time-reversed, time-shifted impulse function. Finally, the sifting property can be applied to the integral of the product of the RF pulse and impulse function to obtain an expression for the GRATER signal $S_{GR}(t)$ in terms of the RF pulse $B_1(t)$ and readout time τ (also slice-select time):

$$S_{GR}(t) \propto B_1(\tau - t) \quad [4]$$

From Equation 4, it can be seen that $S_{GR}(t)$ is proportional to a time-reversed version of the RF pulse. Therefore, the signal $S_{GR}(t)$ can be used to measure the RF waveform under the assumptions stated above.

For in-vivo applications, we anticipate that a sufficiently large homogenous region can be found such that an outer-volume suppression (OVS) pulse can be used eliminate signal from neighboring regions, allowing for a reasonable RF measurement to be made in-vivo. The OVS pulse shown in Figure 1 is the design by Smith and Nayak (14), and includes a B_1 - insensitive non-selective tip-down followed by a cylindrical tip-up pulse. This suppresses signal outside of a cylinder with a diameter of 5 cm. In addition, the GRATER pulse sequence is shown in figure 1. Note that the Fourier transform of $S_{GR}(t)$ gives a slice profile measurement in the small tip angle regime. Therefore, simultaneous multi-slice (SMS) pulses must be excited so that each slice contributes equal signal for an accurate GRATER measurement. In addition, any spurious sidebands must be within the sample volume to be detected by the GRATER method, as illustrated in Figure 2.

METHODS

Experiments were performed on a GE HD23 3T scanner using the body coil. The number of samples in the GRATER waveform was either matched to the programmed waveform or doubled by halving the GRATER readout gradient amplitude (RGA) and extending the readout duration. This allowed for easy comparison of measured vs. expected (programmed) waveforms. Echo times were minimized to mitigate R_2^* effects. RF waveforms were simultaneously measured using GRATER and an external pick-up coil, then adjusted as described in subsequent subsections.

Accuracy of GRATER was explored under near-ideal and non-ideal conditions. To explore GRATER and OVS+GRATER under ideal conditions, experiments were performed on a variety of small flip-angle pulses in a uniform sphere phantom. Accuracy of the OVS +GRATER measurements were determined for different numbers of averages. GRATER adjustment parameters were compared for waveforms acquired on the same day.

To explore GRATER under non-ideal conditions, GRATER was first evaluated with large flip angles in a uniform sphere phantom and compared to Bloch simulation of GRATER waveforms. Second, GRATER was evaluated in non-uniform imaging volumes using GRATER and OVS+GRATER measurements in a fat-water (FW) phantom and in-vivo. PUC measurements were considered the “gold standard” measurement method, and was compared to the GRATER measurement method. Normalized root mean square error (NRMSE) was calculated between programmed and measured waveforms. Raw GRATER data, raw PUC data, code to adjust measured waveforms, and code perform Bloch simulations of GRATER measurements are available (15), Repository: <https://github.com/usc-mrel/GRATER>; Release v1.2: <https://doi.org/10.5281/zenodo.831849>.

GRATER Measurements

If the number of points in the measured GRATER waveform $S_{GR}(t)$ was twice that of the programmed waveform $S_{PW}(t)$ by halving RGA and extending the readout duration, then $S_{GR}(t)$ was first decimated with a Chebyshev Type 1 IIR filter of order 12.

Measured $S_{GR}(t)$ were adjusted for a scale factor A , average relaxation rate R_2^* , average off-resonance ω , initial-phase angle ϕ , and sub-sample time-shifts t_0 by solving a bounded minimum-norm least squares (MNLS) problem. $S_{PW}(t)$ was used as a reference, assuming RF amplifier distortion is not present and thus not concealed. A captures proton density, transmit efficiency, and receiver gain.

The GRATER waveform was modeled as a distorted, time-reversed version of the programmed waveform:

$$S_{GR}(t) \approx A e^{-R_2^* t} e^{-i(\Delta\omega t + \phi)} S_{PW}(\tau - t - t_0) \quad [5]$$

The adjustment parameters were estimated according to:

$$P \in \{A, R_2^*, \Delta\omega, \phi, t_0\} \quad [6]$$

$$P = \min_P \|F^{-1} \left\{ F \left\{ A e^{-R_2^* t} e^{-i(\Delta\omega t + \phi)} S_{PW}(\tau - t - t_0) \right\} e^{-k_z t_0} \right\} - S_{GR}(t) \|_2^2 \quad [7]$$

Parameters were bounded to prevent unreasonable estimates: $A > 0$, $0.2 < R_2^* < 1000 \text{ 1/s}$, $-2\pi 600 < \omega < 2\pi 600 \text{ rad/s}$, $-\pi < \phi < \pi$, and $-10 < t_0 < 10 \text{ }\mu\text{s}$. Initial values were $A = \max(\text{abs}(S_{GR}(t)))/\max(\text{abs}(S_{PW}(t)))$, $R_2^* = 1000 \text{ 1/s}$, and $t_0 = 0 \text{ }\mu\text{s}$. Choosing a high initial R_2^* prevented finding local-minimum solutions of this parameter. Because ω and ϕ adjusted complex GRATER data and were more likely to produce local-minimum solutions, 10 equally-spaced initial values were chosen for these two parameters, and parameters that gave lowest NRMSE were kept. The GRATER waveform was adjusted as $S_{GR,A}(t)$:

$$S_{GR,A}(t) = F^{-1} \left\{ F \left\{ 1/A e^{R_2^* t} e^{i(\Delta\omega t + \phi)} S_{GR}(t) \right\} e^{k_z t_0} \right\} \quad [8]$$

The transmitted RF envelopes in this study were real and so the real part of the adjusted waveform was compared with the programmed waveform and PUC measurements. Previous approaches have noted that measurement then predistortion of the real RF pulse is a simple, sufficient way to reduce undesired higher harmonics (2), and the ultimate intended application of GRATER is for use with predistortion techniques.

Pick-Up Coil (PUC) Measurements

PUC measurements were demodulated and filtered similarly to the method described by Zhu et al (2) with the following exceptions. First, the modulated RF data was bandpass filtered to allow ± 5 MHz around the center frequency. Second, the demodulated RF data was low-pass filtered with a cut-off frequency of 200 KHz. Lowering the range of the bandpass filter and lowering the cutoff frequency of the low-pass filter reduced noise without compromising the shape of the measured waveform. Third, a bounded MNLS optimization problem was solved and corrected for amplitude, timing, and center frequency offsets. This problem was similar to the GRATER bounded MNLS problem, except that $R_2^* \approx 0$.

RF Pulse Design

Table 1 describes the parameters of the RF pulses used in each experiment. Single-band RF pulses were generated in MATLAB using the function `dzrf()` from the `rf_tools` software package based on (16). The sampling period was 4 μ s. Then, the single-band pulse was multiplied by a sum of complex exponentials, $B(t)$, to create multi-band pulses. The sum followed the form

$$B(t) = \sum_i e^{i\omega(G, z_i)} \quad [9]$$

where z_i represents the slice location of an i -band pulse.

Near-Ideal Conditions

Measurements were made in a 27 cm diameter uniform sphere with several multi-band pulses to demonstrate GRATER in near-ideal conditions. Pulse parameters: 2 ms pulses; 500 points; TBW=2,4,6, or 8; 2-band with FA=30°, 3-bands with FA=20°, 4-bands with FA=15°, or 5-bands with FA=12°.

To ensure each excited slice was contained within the 27 cm volume and measureable by GRATER, and to ensure that signal-producing volume came from the linear region of the gradients to avoid side-band amplitude weighting, pulses were designed to have slice centers within ± 5 cm of the center of the phantom. Because the different slices in the uniform sphere phantom could contribute different signal, OVS+GRATER measurements were obtained and compared to GRATER measurements. To account for limited SNR with a limited excited volume, multiple averages were obtained and NRMSE was calculated for measurements using averages of 2:2:64 GRATER measurements. The NRMSE for different averages was fitted according to $\%NRMSE = m / \sqrt{\# \text{ averages}} + b$ where A represents the fitted error floor and B represents the rate of error decay.

To measure high-frequencies in the GRATER-measured waveforms, the amplitude of the GRATER readout gradient was halved to effectively double the sampling period of the GRATER waveform. Results were compared to measurements obtained with a sampling period matched to the transmitted waveform.

To assess the consistency of MNLS-determined adjustment parameters, values were calibrated and compared for each pulse in GRATER measurements using matched RF sampling and transmit periods.

Non-Ideal Conditions: Large Flip Angles

GRATER measurements and Bloch Simulations of GRATER measurements were compared to evaluate GRATER outside the small-tip regime (17). To rule out error in GRATER measurements due to sources other than large flip angles, a uniform sphere phantom was used. A real single-band (TBW=4) RF pulse with flip angles ranging from 5° to 90° in 5° increments was measured. This simple pulse was used to isolate and identify the predictable errors in large flip-angle GRATER measurements from other sources of error.

Bloch Simulations were performed using a sampling period of $4 \mu s$, $T_1 = 2000 \text{ ms}$, $T_2 = 200 \text{ ms}$, gradient amplitude $G = 0.733983 \text{ G/cm}$, and z-positions = 30: 0.1: 30 *cm*. Off-resonance was assumed to be negligible. After simulating RF excitation in the presence of a gradient, the magnetization was calculated every $4 \mu s$ for each z-position during a subsequently inverted gradient to simulate the GRATER measurement. Then, the final GRATER measurement was calculated as the 1D temporal signal averaged over each z-position (i.e. the whole simulated imaging volume).

GRATER measurements and Bloch simulations of GRATER measurements were adjusted by solving the bounded MNLS problem described above with the programmed waveform, divided by its maximum amplitude, as reference. This scaling was done to emphasize errors in the shape of GRATER measurement and Bloch simulation of the measurement. To test the predictability of GRATER measurement error due to deviations from the small-tip approximation, NRMSE between GRATER and simulations of GRATER measurements were compared.

Non-Ideal Conditions: Inhomogeneous Objects

To evaluate GRATER in inhomogeneous objects with high off-resonance, a fat-water (FW) phantom was used to compare RF measurements using 1) GRATER, 2) OVS+GRATER, and 3) the PUC method in regions containing 1) water only, 2) fat only, and 3) both fat and water. Measurements were made in a 2-band, 1.28 ms, 320 point, TBW=4 RF pulse with FA= 15° . GRATER measurements were made without averaging and with matched sampling and transmit rates.

To demonstrate GRATER in an in-vivo imaging volume, the same 2-band pulse in the FW phantom experiments was measured using 1) GRATER, 2) OVS+GRATER and 3) the PUC method in an axial brain slice above the ventricles in two healthy volunteers (M, 27 and 30). Each subject was screened and provided written informed consent with approval from the Institutional Review Board.

RESULTS

Near-Ideal Conditions

GRATER measurements were made in a variety of pulses using the uniform sphere phantom. NRMSE of GRATER measurements increased for higher numbers of bands and time-bandwidth products in Figure 3A. Higher error comes from unequal signal contribution from each excited band and is described in Figure 2. For example, the waveforms matched most closely in the 2-band, TBW = 2 RF pulse, where GRATER vs. programmed and PUC vs. programmed waveforms had 1.1% and 0.9% NRMSE, respectively. NRMSE was highest in the 5-band, TBW = 8 RF pulse, where NRMSE between GRATER vs. programmed and PUC vs. programmed waveforms had 6.1% and 2.1% NRMSE, respectively. To lower NRMSE in GRATER, two strategies were shown to be helpful: 1) averaged OVS+GRATER measurements and 2) lowering RGA and extending the readout duration to acquire more points in the GRATER-measured waveform.

Figure 3A shows lower NRMSE with 64 averaged OVS+GRATER measurements vs. 64 averaged GRATER measurements. The biggest improvement was seen in the 5-band, TBW = 8 RF pulse with 3.8% reduction in NRMSE from 6.1% to 2.4%. Over the 16 RF pulses with parameters described in Table 2, mean $\pm$ standard deviation of NRMSE was $4.4 \pm 1.7\%$ NRMSE for averaged GRATER measurements and $1.9 \pm 0.60\%$ NRMSE for averaged OVS+GRATER measurements. Furthermore, the clear trend of higher NRMSE for higher numbers of bands and higher TBW product in GRATER measurements is not seen in OVS+GRATER measurements. For comparison, mean $\pm$ standard deviation was $1.5 \pm 0.30\%$ NRMSE with the PUC method.

Figure 3B shows improvement with lowered RGA as a function of number of averaged OVS+GRATER measurements in the 5-band, TBW = 8 RF pulse. Over 64 averages, NRMSE decreased from 2.4% for RGA = -G to 1.5% NRMSE for RGA = -G/2. After fitting the curves of NRMSE vs. # averages to the equation $\%NRMSE = m / \sqrt{\# \text{ averages}} + b$ the fitted error floor b decreased from 1.9% to 0.9% NRMSE for RGA = -G and RGA = -G/2, respectively. Furthermore, the fitted rate of error decay m increased from 3.7% to 4.2% NRMSE for RGA = -G and RGA = -G/2, respectively.

Figure 4 visualizes the best-measured improvement of the 5-band, TBW=8 RF pulse by combining both strategies of 64 averages of OVS+GRATER combined with RGA=-G/2 to lower NRMSE. GRATER measurements without OVS, PUC measurements, and the programmed waveform are shown for comparison. Figure 4A shows that the errors in GRATER measurement are most prominent in the high-frequency peaks and valleys of the RF lobes, due to the unequal signal contribution for each of the 5 bands. This error is greatly reduced with OVS. The difference between measured and the programmed waveform are also shown in figure 4B. There is clear structure to the difference waveform of GRATER without OVS. This structure is reduced with OVS however the cause of the remaining structure is unresolved.

Table 2 shows the consistency of MNLS-determined adjustment parameters determined for each of the 16 SMS RF pulses in GRATER measurements using matched RF sampling

and transmit periods, all acquired during the same scan session. Pre-scan was run once for these experiments and CV was low for A . The calculated R_2^* values were all larger than the phantom's true R_2 of 33 1/sec. With a good shim, $\omega \approx 0$ in all cases, t_0 was consistent to within 7.1% CV. Of the adjustment parameters, ϕ varied the most from scan to scan.

Non-Ideal Conditions: High Flip-Angles

Figure 5 shows results of high flip-angle experiments in Bloch simulations of GRATER measurements and experimental GRATER measurements, plotted over the same range to emphasize the shape of the GRATER measurement compared to the programmed waveform. Both plots show the programmed RF pulse as a reference in dashed-cyan. RF pulses with flip angles 40° are plotted in blue, $45\text{--}65^\circ$ in green, and 70° in red. This demonstrates that GRATER measurement error increases for increasing flip angles. GRATER-measured and Bloch-simulated measurements matched to $<2.4\%$ for each flip angle pair. This implies GRATER measurement error occurred in a patterned, predictable way.

Non-Ideal Conditions: Inhomogeneous Objects

Figure 6 compares RF measurements of a FW phantom using GRATER, OVS+GRATER, and the PUC method to evaluate GRATER in inhomogeneous objects with high off-resonance. The imaging slice is shown without OVS in Figure 6A where 'F' and 'W' represent fat and water, respectively. The imaging slice is shown with OVS in Figure 6B to demonstrate the ability of the OVS pulse to select a 5 cm diameter region. Figure 6C shows the programmed 1.28 ms, 320 point, 2-band, and TBW=4 RF pulse in black, the PUC method in red, and the OVS+GRATER measurement in dashed black.

Figure 7 compares RF measurements in two healthy subjects using GRATER, OVS+GRATER, and the PUC method. Figure 7A shows an axial slice above the ventricles was excited in the brain for GRATER measurements. Figure 7B shows an excited 5 cm cylinder in the center of the axial slice to avoid off-resonance at the brain-skull interface. Figure 7C shows measurements of a 1.28 ms, 320 point, 2-band, and TBW=4 RF pulse against the programmed waveform. The PUC, GRATER, and programmed waveform all matched to $<3.0\%$ difference. The PUC and OVS+GRATER waveform matched to $<4.5\%$.

Figure 8 summarizes NRMSE values for FW phantom and in-vivo experiments. There was $<1.5\%$ difference in PUC vs. programmed measurements. PUC vs. GRATER measurements differed by 58% in the fat+water of the FW phantom and $<12\%$ NRMSE in all other cases. PUC vs. OVS+GRATER measurements differed by $<6.4\%$ NRMSE in the water of the FW phantom and in the brain. While OVS+GRATER vs. PUC had lower NRMSE than GRATER vs. PUC in the FW phantom, an OVS pre-pulse increased NRMSE of GRATER measurements in the brain. Mean NRMSE in inhomogeneous objects of PUC vs. programmed was $1.2 \pm 0.2\%$, PUC vs. GRATER was $17 \pm 25\%$, and PUC vs. OVS+GRATER was $5.1 \pm 1.1\%$.

DISCUSSION

This study has successfully demonstrated measurement in a variety of small-tip RF waveforms to within $<2.4\%$ NRMSE using averaged OVS+GRATER measurements in

uniform volumes. It has also demonstrated that acquiring more points in the measured waveform further lowered NRMSE. In non-uniform volumes, NRMSE <6.4% was achieved using OVS+GRATER without averaging. A variety of methods to further improve the GRATER technique form the core of this discussion.

NRMSE was used in this study as a generic metric to describe error between any RF waveforms or measurements and to establish GRATER's accuracy under different conditions. NRMSE may not be the ideal metric for RF pulse correction and application-specific metrics could be more useful. For example, spurious side lobe excitation may be more appropriate to evaluate SMS-RF pulses, or stop-band suppression for spectral-editing RF pulses. Regardless of the specific metric, the accuracy of GRATER would have to match or surpass the accuracy of the PUC method to be a successful measurement technique and detect subtle RF amplifier nonlinearity. Therefore, it is important to acknowledge GRATER's successes and investigate ways to overcome current limitations.

GRATER and PUC measurements matched very closely in the uniform sphere phantom for small-flip angle pulses with two bands, such as the 2msec, 2-band, TBW=2 RF pulse. However, error in GRATER measurements increased in RF pulses with higher numbers of bands due to the unequal signal coming from each excited slice. These RF pulses may have also contained error that GRATER was unable to fully capture at the current sampling period of 4 μ s (i.e. readout bandwidth of 125 kHz). This limitation is best seen the 2 msec, 5-band, TBW=8 RF pulse, where GRATER error is highest on either side of the main lobe. NRMSE was reduced by 1) using an OVS prepulse to obtain equal signal from each slice, 2) averaging to overcome the reduced SNR in each slice due to OVS, and 3) lowering the amplitude and extending the duration of the readout gradient to traverse excitation k-space more slowly and acquire more points in the GRATER-measured waveform. While the error has been reduced, the difference between the programmed and best-measured waveform still has structure. This could be due to the need for an even faster sampling period through a further lowered and extended readout gradient or increased receive sampling rate. This could also be explained by imperfect OVS pulse performance.

For measurements in inhomogeneous objects, recall GRATER is a proton-density weighted measurement. Because of this, GRATER measurements will be best in areas where the excited region has as uniform proton density as possible. Therefore, error measurement the chosen slices could be due to signal coming from inhomogeneous tissues, i.e. fine structures in the brain. While one OVS pre-pulse is demonstrated in this study (14), GRATER in different situations may benefit from selection of different size volumes. Spectral pre-pulses could also be used, such as a water saturation pre-pulse followed by GRATER measurement in subcutaneous fat near a receive coil.

OVS+GRATER is a time-reversed measurement and was clearly emphasized in GRATER measurements with fast signal attenuation in the fat-water phantom and is not likely to be resolved with averaging. It could be seen that noise in the end of the measurement became more prominent. To resolve this error, different sections of the RF pulse could be recorded in successive GRATER measurements, then combined to produce a complete measurement. More signal remained from the RF measurement towards the end of the OVS+GRATER

measurement in the brain than in the FW phantom. This indicates different R_2^* of the two volumes.

Compared to GRATER, OVS+GRATER more accurately captured RF waveforms in the FW phantom, but not in the brain. Gains in excited volume uniformity with an OVS pre-pulse were not enough to offset the decrease in signal-to-noise ratio caused by limiting the region of excited tissue with an OVS pulse. While OVS+GRATER measurement averaging is a viable option, as demonstrated in the uniform sphere experiments, adjusting the GRATER excitation and readout gradient amplitudes may further reduce NRMSE. If the amplitudes are decreased, slice-thickness and SNR could be increased in volumes with low signal. However, this may decrease excited sample uniformity and increase through-slice dephasing. If the amplitudes are increased, errors caused by erroneous phase in SMS bands due to B_0 variation will be mitigated by making the excited volume small in the z direction. In addition, potential amplitude weighting of side-bands due to non-linearity in the selection gradient, similar to the pile-up artifacts seen in scans with non-linear frequency position mapping, could be reduced.

The waveforms in this study were designed to establish and evaluate feasibility of the GRATER method in phantoms and in-vivo, and were not designed to push the RF amplifier into its non-linear regime. If one is using GRATER to correct for RF amplifier non-linearity, it is of concern that adjustments relative to the ideal programmed waveform may conceal waveform distortions. The consistency of adjustment parameters has been demonstrated from scan to scan, and this decreases concern. So, GRATER recon may be made more efficient by re-using parameters from scan-to-scan.

Despite all of this, comparing or even replacing MNLS-determined adjustment parameters with sequence-based measurements will be useful in the future. For example, simple pulse sequences can be used to measure or correct for R_2^* , ω , and t_0 instead of estimating them in a bounded MNLS problem. More specifically, R_2^* , ω , and ϕ can be measured with an FID. In addition, ω can be measured and corrected for using a B_0 mapping technique. Also, t_0 between the GRATER measurement and PUC waveform can be corrected with gradient delays. Finally, to reduce noise in GRATER using averaging while simultaneously measuring R_2^* , the GRATER read-out waveform can be repeatedly inverted and data can be acquired during each inversion to acquire multiple GRATER measurements. These measurements will be weighted with the R_2^* relaxation rate. Timing errors would likely occur with reverse polarity readouts, and so other adjustment parameters, especially t_0 , would have to be calculated for each readout.

Finally, GRATER may be useful for predistortion with large imaging volumes and small flip-angle RF pulses, such as short SMS pulses with a high number of bands that push the RF amplifier into its non-linear region. For large flip-angle pulses, it has been demonstrated that GRATER measurement error and Bloch simulation of GRATER measurement error increased as the flip angle increased from 30° to 90° and that GRATER measurement error was predictable by simulation. While GRATER's potential for RF measurement has been demonstrated, its applicability for use with predistortion techniques is a topic of future work, both in small and large flip-angle RF pulses.

CONCLUSIONS

In conclusion, GRATER is a promising new technique for RF envelope measurement. Compared to the traditional pick-up coil technique, GRATER is fast, requires no hardware, and no synchronization. GRATER measured the 2-band $TBW = 2$ RF pulses accurately compared to the PUC method under ideal conditions. Including OVS pre-pulses, averaging measurements, and acquiring more points in the GRATER waveform were shown to increase accuracy for pulses with higher numbers of bands and TBW. In large flip angles, GRATER measurement error occurs in a way that is predictable by Bloch simulation. In non-uniform volumes, an OVS pre-pulse may select a uniform region and improve GRATER measurements. GRATER may be useful in pre-scan calibration, and for measurement and pre-compensation of RF amplifier nonlinearity.

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Figure 1.

GRATER RF measurement consists of an (A) optional OVS pre-pulse and (B) GRATER with a simulated asymmetric RF pulse $B_1(t)$. The OVS pre-pulse (14) consists of a $+90^\circ$ BIR-4 tipdown, a -90° spiral tipback pulse, and a gradient spoiler. GRATER consists of $B_1(t)$ in the presence of a constant gradient followed by signal acquisition in the presence of the same gradient, inverted. The received GRATER signal $S_{GR}(t)$ (red) is a time-reversed version of $B_1(t)$ (blue). (C) OVS and a slice-selective $B_1(t)$ excite volume with a single coil. $S_{GR}(t)$ is then acquired with the same coil.

Figure 2.

Cartoon of excited slices from a 5-band SMS RF pulse in a spherical phantom. The Fourier transform of $S_{GR}(t)$ gives a slice profile measurement in the small tip angle regime. (A) If a GRATER measurement is obtained, artifacts will result from unequal signal contribution from each band (purple). (B) If an OVS+GRATER measurement is taken, each band will contribute equal signal but SNR will be lower. (C) If waveform distortion is present, undesired bands can become excited (purple, hashed) and must be contained within the imaging volume to be detected.

Figure 3.

NRMSE of uniform sphere experiments for SMS pulses with different numbers of bands (# bands) and time-bandwidth (TBW) products. (A) NRMSE for 64 averaged GRATER and OVS+GRATER with $\text{RGA} = -G$, the negative excitation gradient amplitude. GRATER NRMSE was higher with more slices and was reduced with OVS to 2.4% (black dashed line) by up to 3.8% (red arrow). NRMSE in PUC was 2.1%. (B) NRMSE decreases with averaging of OVS+GRATER in a 5 band, $\text{TBW}=8$ pulse for $\text{RGA}=-G$. It decreases more and faster for $\text{RGA}=-G/2$. Data was fitted to $\% \text{NRMSE} = m / \sqrt{\# \text{averages}} + b$ (solid lines). Fitted error floors are shown (arrows).

Figure 4.

GRATER using a 5-band, TBW=8 RF pulse in a uniform sphere. (A) A (black) programmed RF pulse was measured using (black) PUC, and 64 averages with $\text{RGA} = -G/2$ of (blue) GRATER, and (cyan) OVS+GRATER. The zoomed-in lobes in the GRATER waveform show error from unequally excited bands and can be seen more clearly with the difference between waveforms in (B). Compared with programmed waveforms and PUC, GRATER matches with $<5.7\%$ NRMSE and $<1.5\%$ with OVS+GRATER. There is structure in the difference between programmed and OVS+GRATER measurements (arrows) and the source of this error is unresolved.

Figure 5.

(A) Experimental GRATER measurements and (B) Bloch simulations of GRATER measurements of a single-band RF pulse in a uniform sphere phantom with flip angles in 5° increments from 5° to 90° , adjusted so the programmed pulse, divided by its maximum amplitude, was used as reference. Measurements with a small flip angle (5° FA 40°) are shown in blue, in-between flip angles (45° FA 65°) in green, and large flip angles (70° FA 90°) in red. NRMSE between GRATER measurements and simulations for a given flip angle was $<2.4\%$. Top row shows the total waveform. The boxed-off portions are shown in the bottom row, zoomed.

Figure 6.

GRATER in a fat-water phantom. The imaging slice (A) without and (B) with OVS. 'F' and 'W' in (A) represent fat and water, respectively. (C) A (black) programmed 1.28 ms, 320 point, 2-band, and TBW=4 RF pulse was measured using (green) PUC and (magenta) OVS +GRATER. NRMSE was <6.4% between programmed, PUC, and OVS+GRATER measurements. OVS+GRATER is a time-reversed measurement (see Equation 2); noise increases towards the end of the measurement (arrow).

Figure 7. GRATER in the brain of one volunteer. The imaging slice (A) without and (B) with OVS. An imaging slice was chosen superior to the ventricles. Measurements of a 1.28 ms, 320 point, 2-band, and TBW=4 RF pulse using 1) the PUC method and 2) the OVS+GRATER method are plotted against the programmed waveform in (C). PUC, GRATER, and programmed waveforms match to <3.0% NRMSE. OVS+GRATER vs. PUC had <4.5% NRMSE.

Figure 8.

NRMSE of experiments in non-uniform samples: the fat-water (FW) phantom, subject 1 (S1), and subject 2 (S2). NRMSE was calculated between the PUC method and 1) the programmed waveform, 2) the measured GRATER waveform, and 3) the measured OVS +GRATER waveform. PUC vs. GRATER had 58% NRMSE in fat+water. OVS improved the accuracy of GRATER to 6.4%. PUC vs. programmed waveforms had <1.5% NRMSE.

Summary of RF pulse parameters used in a uniform sphere, fat-water (FW) phantom, and in-vivo experiments: number of excited bands (# bands), duration (Dur), bandwidth per band (BW), time-bandwidth product (TBW), flip angle (FA), slice center (SI Ctr), and slice thickness (SI Thk).

Table 1

Expt. ^a	# bands	Dur (ms)	TBW	BW (Hz)	FA (°)	SI Ctr(s) (cm)	SI Thk (cm)
Uniform sphere (ideal conditions)	2	2	2:2:8	TBW/2e-3	30	±2.5	1
	3	2	2:2:8	TBW/2e-3	20	0, ±3.3	1
	4	2	2:2:8	TBW/2e-3	15	±1.25, ±3.75	1
	5	2	2:2:8	TBW/2e-3	12	0, ±2.5, ±5	1
Uniform sphere (large FA)	1	1.28	4	3125	5:5:90	0	1
FW & in-vivo	2	1.28	4	3125	15	±2.5	1

Summary of adjustment parameters for GRATER waveforms without OVS or averaging in uniform sphere experiments in the same scan session with the same pre-scan. Parameters were solved with a bounded MNLS problem for pulses with different numbers of bands (# bands) and time-bandwidth (TBW) products. The bottom two rows show the mean and coefficient of variation (CV) for each parameter value. CV was low for A . Calculated R_2^* values were larger than the phantom's R_2 of 33 1/sec. With a good shim, $\omega \approx 0$ in all cases. ϕ varied from scan to scan. t_0 was consistent to within 7.1% CV.

Table 2

# bands, TBW	A (a.u.)	R_2^* (1/s)	ω (rad/s)	ϕ (rad)	t_0 (μ s)
2,2	.69	100	-0.0022	-0.15	-0.62
2,4	.68	110	-0.0023	-0.15	-0.60
2,6	.68	130	-0.0027	-0.13	-0.63
2,8	.67	140	-0.0032	-0.11	-0.63
3,2	.69	86	-0.0023	-0.15	-0.72
3,4	.70	90	-0.0025	-0.14	-0.66
3,6	.69	97	-0.0031	-0.11	-0.56
3,8	.68	110	-0.0036	-0.09	-0.60
4,2	.68	110	-0.0025	-0.13	-0.63
4,4	.68	110	-0.0030	-0.11	-0.57
4,6	.67	130	-0.0032	-0.10	-0.56
4,8	.66	140	-0.0030	-0.12	-0.67
5,2	.69	100	-0.0025	-0.12	-0.66
5,4	.68	100	-0.0024	-0.14	-0.66
5,6	.68	120	-0.0029	-0.12	-0.62
5,8	.66	140	-0.0060	-0.01	-0.68
MEAN	.68	110	0.0030	-0.12	-0.63
CV (%)	2.8%	16.3%	30%	28%	7.1%