Efficient Gradient Waveform Design With 0th and 1st Moment Control for Flow Compensated bSSFP

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Introduction: Time-efficient gradient waveforms with pre-defined 1st moments (M_1) can be difficult to design. These gradients are at the core of many techniques such as phase contrast and flow-compensated acquisitions. A new method for designing hardware-optimized gradient waveforms is presented that works in both logical and physical coordinate systems and operates at the physical limits of the gradient hardware [1,2]. The method works directly on a rasterized time scale, and yields complete control of the M_0 (0th moment), or M_0 and M_1 of waveforms. As an example, simulations are used to design an efficient balanced steady-state free precession (bSSFP) sequence, along with partially and fully M_1-nulled(M_1=0 mT/m*us^2) variants that are useful for flow-compensated bSSFP.

Theory: The design strategy originates from [1] which states that (1) the linear combination of two piecewise linear waveforms yields a waveform whose M_0 (and M_1) is the weighted sum of the originals; (2) any desired M_0 (or M_1) that is bounded by the M_0's (or M_1s) of individual waveforms can be generated by taking a linear combination of the waveforms. The two source waveforms are defined automatically at the gradient raster time points, so the combined waveform is also solely defined at the raster time points. *M_0 Design:* An iterative algorithm is used to search for the minimum pulse width (PW) necessary to achieve the target M_0 given boundary conditions (starting/ending gradient amplitude G_{start}, G_{end}), start time (t_0) and time delays (Δt_{pre}, Δt_{post}) and hardware limitations (max gradient amplitude G_{max}, max gradient slew-rate SR_{max}, and scanner raster time Δt) (Fig 1A,B). For any given PW, the algorithm produces two waveforms: W_{max} and W_{min} which represent the max and min M_0's (and M_1's) that can be achieved in that time. *M_0+M_1 Design:* W_{max} and W_{min} from M_0 Design do not fully constrain the boundaries of possible (M_0,M_1) *combinations* attainable in the PW. A "family" of waveforms is generated (Fig 1C,D) based on W_{max} and W_{min}. When all family moments are plotted on the M_0-M_1 plane (Fig 2), the space of attainable moments is circumscribed. Each point of the "eye" represents one of the waveforms of the generated family. If the desired (M_0,M_1) combination is within this space, the desired waveform can be created by linear combination of family members. Otherwise, PW is increased and the process repeated. The algorithm returns a waveform that matches desired M_0 and M_1 exactly and can be constructed in real-time.

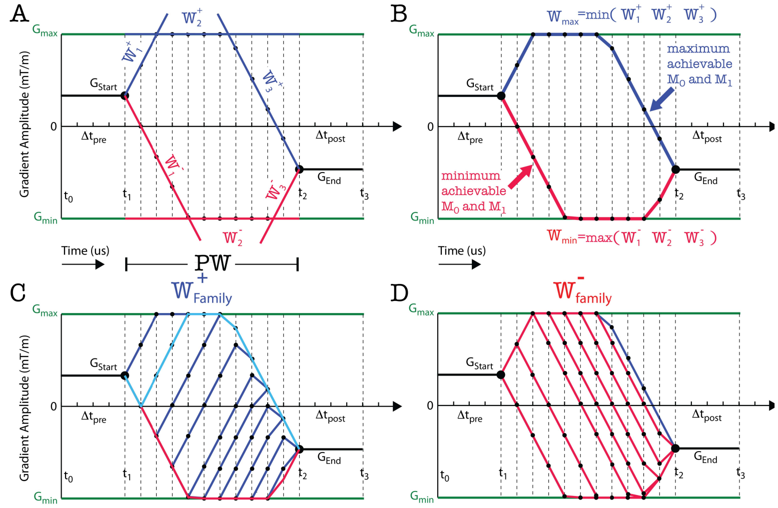

Figure 1: (A)M_0 waveform design begins by creating three separate waveforms for a given pulse width (PW) and gradient hardware limitations: W_1 rises from G_{start} at the maximum slew rate SR_{max}. W_2 is a flat waveform at the max gradient (G_{max}). W_3 rises from G_{end}, in reverse, at SR. (B) Taking the point-wise min yields W_{max}, the waveform with the maximum achievable M_0 and M_1. The same treatment is repeated for the negative waveforms, yielding W_{min}. Waveforms are defined at each raster point (dotted lines) and therefore automatically take into account the gradient raster times. (C&D) Using W_{max} and W_{min}, positive and negative waveform families, W^+_{family} and W^-_{family} are generated. For example, the first member of W^+_{family} is generated by taking the first segment of W_{min} and then following M_0 design (light blue in C). When all waveforms are considered, they circumscribe an area in M_0-M_1 space that represents M_0/M_1's achievable by linear combinations of members of the two families.

Methods: Three sequences of varying levels of motion compensation were designed (Fig 2). **Seq A** is standard bSSFP, fully M_0-balanced, with free M_1 behavior. Due to temporal symmetry in readout (RO) and slice selection (Ss), M_1 is automatically nulled along those axes at both TE and TR. **Seq B** is M_1-balanced at TE for all gradients and at TR for RO and SS. It is similar to other flow-compensated bSSFP sequences [2,3,4] with addition of moment nulling of all PEs. **Seq C** is M_1-balanced on all axes at both TR and TE and for all PE steps, and *represents to our knowledge an imaging sequence never presented before.* M_1 characteristics for the 3 sequences can be seen in Table 1. To retain the spin-echo nature of the bSSFP [5], the echo was centered and the PWs of the transition to and from the RF pulse were set equal. Other simulation parameters used in MATLAB were: 4 us per readout point with xres N_x=128-256, 10μs Δt,600 μs RF pulse, 36x36cm^2 FOV, 100% phase resolution, G_{max}=40 mT/m and SR=150 mT/m/ms.

Table 1.	M_1 @ TE RO/PE/SS	M_1 @ TR RO/PE/SS	Transition PW/TR (μs) N_x=128	192	256 pts
Seq A	Free/Free/Free	Free/Free/Free	480/2080	550/2470	610/2470
Seq B	Fixed/Fixed/Fixed	Null/Free/Null	1030/3180	1210/3790	1400/4430
Seq C	Fixed/Fixed/Fixed	Null/Null/Null	1420/3960	1850/5070	2300/6230

Results: The designed sequences can be seen in Fig 2. The TRs and SS to RO transition PWs for various RO resolutions can be seen in Table 1.The fully M_1-nulled sequence **C** increases TR significantly, while the use of temporal symmetry in RO and SS in **B** reduces TR at the expense of control of M1 in the PE axis at TR.

Conclusion: Setting the M_1 at TE can be used to generate flow compensated waveforms or for phase contrast imaging. Nulling the M_1 at TR can prevent artifacts from variable phase accrual on a TR per TR basis, especially for fast flowing spins [4]. The design methods proposed here provide the flexibility to generate efficient bSSFP-based sequences. Though not shown here, the design of waveforms with a particular desired M_1 (e.g. with a given V_{enc} for phase contrast imaging), does not significantly increase scan time, as the most time consuming portion of the fully M_1-nulled sequence is the transition into the succeeding RF pulse. The methods can also be used in real-time imaging: the creation of *any* M_0-M_1 combination is achieved by weighted addition of 4 family member waveforms. [1]

References: [1] Derbsyhire MRM 2010 64(6):1814.[2] Bolster JMRI 1999 10(2):183.[3]Bieri MRM 2005 54(4):901.[4] Zhou JMRI 2010 31(4):863.[5] Sheffler MRM 2003 49(2):395.

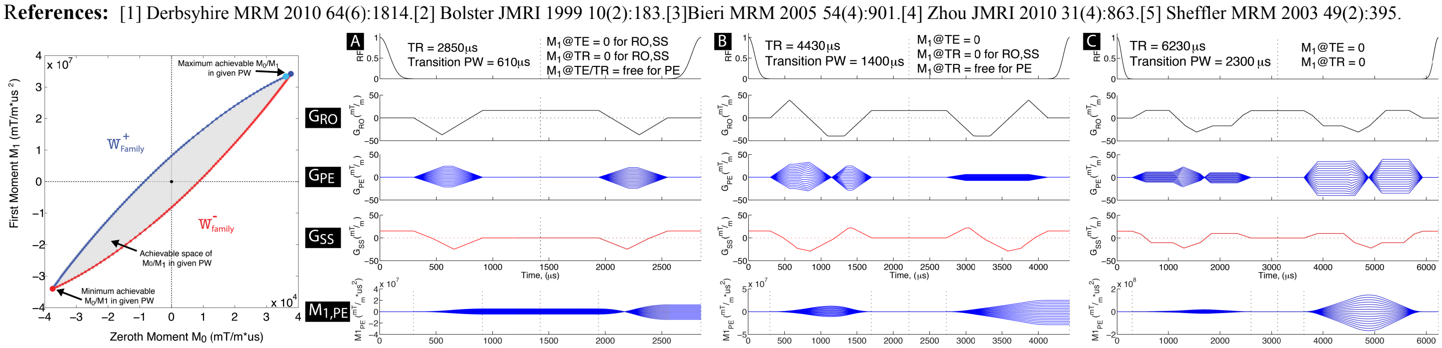

Figure 2: (Left) For each member of waveform W^+_{family} and W^-_{family}, M_0 and M_1 are plotted and the space of achievable desired M_0/M_1 combinations for a given PW is delineated (gray area). Any M_0/M_1 combination can be generated by the appropriate linear combination of members of the two families of waveforms. **Right:** Three different sequences are simulated using the proposed methods: **A** standard bSSFP; **B** M_1-nulled bSSF ; **C** Fully M_1-nulled bSSFP (M1=0 @ TE and @ TR for all 3 axis, for all PEs). As expected, as the M_1-nulling requirements get more stringent, TR increases. Note that **B** is similar to previously published sequences with the addition of M_1-nulling at TE for all PEs. **C** is a new fully balanced sequence which should have the best moment flow-compensation performance. Additionally, both **B** and **C** can be designed to accommodate any desired M_1 (V_{enc}) at TE for phase contrast imaging without significant increases in TR.