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Characterization and suppression of stripe artifact in velocity-selective magnetization-prepared unenhanced MR angiography

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Abstract

Purpose—To characterize and suppress stripe artifact associated with velocity-selective (VS) magnetization for unenhanced magnetic resonance angiography (MRA).

Methods—Extended phase graph formalism was used to show that the stripe artifact contains multiples of the fundamental frequency that is determined by the area of unipolar VS gradient. Four VS preparation pulses whose excitation profiles are spatially shifted by quarter the fundamental period of the stripes, were applied alternately. For further suppression of the artifact, k-space data at $k_z = 0$ were averaged over the four VS preparations. The proposed schemes were tested in a chicken breast phantom and healthy human subjects.

Results—When the standard VS preparation scheme was used, stripe artifact was shown in all the reconstructed images and appeared as artifactual peaks in k-space which corresponded to the first and second order harmonics of the fundamental frequency. Alternate application of the four phase-shifted VS preparation pulses suppressed the stripes but not completely as evidenced by residual erroneous peaks in k-space. After the k-space averaging, the stripe artifact was nearly eliminated.

Conclusion—Stripe artifact in VS-MRA consists of multiples of the fundamental frequency and can be effectively suppressed through alternate application of phase-shifted VS preparations along with k-space averaging.

Keywords

velocity-selective magnetization preparation; non-contrast-enhanced MR angiography; stripe artifact

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Introduction

Velocity-selective (VS) magnetization-prepared MRI has been recently introduced as a promising gadolinium-free angiography approach (1,2). At the core of this approach, hereafter termed VS-MRA, is Fourier-based VS magnetization preparation pulse which excites magnetic spins selectively based on their velocities (3). Unlike earlier flow-sensitive preparation pulses used for subtractive angiography methods (4–7), the Fourier-based VS preparation offers flexible velocity pass- and stop-bands and sharp transition between the two bands, and therefore enables positive angiographic contrast using single acquisition without subtraction. While developed for renal angiography for its first application, VS-MRA has shown great promise for peripheral, cerebral and pedal angiography as well (1,2,8–10).

The earliest version of VS excitation pulse consists of multiple rectangular RF pulses of small flip angle interleaved with bipolar gradients (1,3). This baseline design is short and easy to implement but is prone to excitation profile shifting in proportion to off-resonance. Refocused designs of VS excitation incorporate 180° refocusing pulses between the two unipolar gradients split from the original bipolar gradient, and reduce B_0 -offset-induced phase during each pair of unipolar gradients. In this single-refocused design, however, severe B_1 inhomogeneity causes distortion of velocity passband, which in turn results in signal loss in arterial blood. The latest studies on VS excitation pulse design have shown that multiple-refocused designs substantially improve the immunity to both B_0 and B_1 offsets, being robust to wide ranges of the field errors (8,10,11).

Although the velocity selectivity has become quite robust against field offsets with the use of multiple refocusing pulses, another issue that remains unresolved is erroneous spatial selectivity which appears specifically as stripes repeated in the direction of the VS gradient. Similar stripe artifact was reported in images obtained from flow-sensitive dephasing (FSD) magnetization preparation which is a simple case of Fourier-based VS preparation with one VS excitation step (6). Mathematical analysis of the FSD preparation revealed that the spatial period of the stripes is related to the area of the FSD gradient. Based on the assumption that the stripe artifact created in VS-MRA also has single frequency component, a recent study proposed to play two VS preparation pulses successively which have the same velocity selectivity but spatial selectivity shifted by half the period of the stripes (11). In this study, we first analyze the generation of the stripe artifact using extended phase graph analysis, and show that the stripes actually contain not only the fundamental frequency determined by the area of the VS gradient but higher-order components with multiples of the fundamental frequency. Based on this finding, we propose and test strategies for effective suppression of the artifact in phantom and healthy human subjects.

Methods

Stripe artifact in VS-MRA

Fourier-based VS magnetization preparation concatenates multiple VS excitation steps each of which consists of a hard RF pulse, a unipolar gradient, a refocusing module, and a reversed unipolar gradient (Fig. 1) (1,2). The refocusing module denoted by the dotted grey

box in Fig. 1, consists of one or multiple 180° rotations interleaved with additional unipolar gradients while the case of two 180° pulses is shown in the figure. After excitation by the preceding hard RF pulse, spins get dephased to a varying degree that depends on their velocities by the unipolar gradients. The amount of this dephasing determines how constructively the subsequent hard RF pulse works on the spins, thereby contributing to the net flip angle in a velocity-dependent fashion.

Ideally, VS excitation does not involve spatial selectivity. In each VS excitation step, spatial position makes no contribution to the spin's dephasing since the effective area of unipolar gradients is zero. However, if the refocusing module involves any error (mostly due to B_0 and B_1 field offsets), the effective area of unipolar gradients is no longer zero, which will have spins spatially modulated during each VS excitation step and eventually yield artifactual stripes in reconstructed images (11). It is apparent that the frequency of such spatial modulation at the end of the 1st excitation step (i.e. the location 'e' in Fig. 1) is determined by the area of unipolar gradient.

$$k_1 = (\gamma/2\pi) \left(\int_0^T G_{uni}(\tau) d\tau \right) \quad [1]$$

With the erroneous dephasing repeated over multiple excitation steps, the configuration of spins' phases becomes too complicated to be easily estimated at the end of the entire excitation pulse sequence.

Extended phase graph analysis

To come up with strategies to suppress stripe artifact, it is necessary to model and characterize the stripes under assumption of the presence of refocusing errors. For this purpose, we choose to use the extended phase graph (EPG) formalism which can analyze the evolution of the erroneous dephasings by representing the configuration of spin *ensemble* as a linear superposition of basis dephasing states, namely F_n and Z_n states (12–19). The F_n state represents a group of transverse magnetizations dephased in proportion to positions along the axis of the gradient field played, where n represents the amount of the dephasing in number of cycles. The Z_n state represents a group of longitudinal magnetizations with sinusoidal amplitude variation, where n represents the number of sinusoidal cycles.

The evolution of spin ensemble configuration is determined by the actions of gradient and RF pulses on the F_n and Z_n states. First, gradient pulses dephase the spins, therefore changing the dephasing index n of the F_n state but does not affect the Z_n state (assuming T_1 relaxation is negligible). For convenience of analysis, we define an increase of the index n by 1 as phase accrual by one positive unipolar gradient used in VS preparation pulses. Second, RF pulses decompose each of F_n and Z_n states into a linear superposition of F_n and Z_n states while not changing the order of either state (16,19):

$$F_n \rightarrow \cos \frac{2\alpha}{2} F_n + e^{-2i\phi} \sin \frac{2\alpha}{2} F_{-n} + \frac{i}{2} e^{-i\phi} \sin \alpha Z_n$$

$$F_{-n} \rightarrow e^{2i\phi} \sin^2 \frac{\alpha}{2} F_n + \cos^2 \frac{\alpha}{2} F_{-n} + \frac{i}{2} e^{i\phi} \sin \alpha Z_n \quad [2]$$

$$Z_n \rightarrow -ie^{i\phi} \sin \alpha F_n + ie^{-i\phi} \sin \alpha F_{-n} + \cos \alpha Z_n$$

Where superscripts $-$ and $+$ denote before and after RF excitation; α and ϕ represent flip angle and phase of the RF pulse, respectively.

The evolution of the spin ensemble states can be described for each of the transitions from points a through f in Fig. 1 as follow:

- i. $a \rightarrow b$: The 1st hard RF pulse splits initial longitudinal magnetization (Z_0) into transverse (F_0) and longitudinal magnetizations (Z_0). The specific coefficients for the two new states are ignored as they are of the same order of amplitude.
- ii. $b \rightarrow c$: Unipolar gradient dephases the transverse magnetization and increases the dephasing index from 0 to 1 while not affecting the longitudinal magnetization.
- iii. $c \rightarrow d$: Imperfect refocusing module can be approximated by erroneous excitation with tiny flip angle ϵ and phase. Using $\cos \epsilon \approx 1$ and $\sin \epsilon \approx \epsilon$ when ϵ is small, the amplitude orders of the decomposition coefficients can be written as follow.

$$F_n \rightarrow O(\epsilon^0)F_n + O(\epsilon^2)F_{-n} + O(\epsilon^1)Z_n$$

$$F_{-n} \rightarrow O(\epsilon^2)F_n + O(\epsilon^0)F_{-n} + O(\epsilon^1)Z_n \quad [3]$$

$$Z_n \rightarrow O(\epsilon^1)F_n + O(\epsilon^1)F_{-n} + O(\epsilon^0)Z_n$$

where $O(\epsilon^k)$ means amplitude order of ϵ^k up to a constant. Note that the phase of the erroneous excitation does not affect the amplitude of the ensemble states according to Eq. 2. Also note that the excitation with tiny angle ϵ can approximate various types of imperfect refocusing modules with flexible choices for the number and type of 180° pulses.

- iv. $d \rightarrow e$: Negative unipolar gradient decreases the dephasing index of the transverse states.
- v. $e \rightarrow f$: The second hard RF pulse decomposes the ensemble states at point e into eight independent states based on Eq. 2.

The EPG diagram was developed for the rest of the pulses in a similar way though not shown for brevity. Ensemble states with orders of amplitude lower than ϵ^3 were dropped during the analysis. While all the independent ensemble states derived at the end of the pulse sequence (point g) are shown on the bottom right side of Fig. 1, longitudinal states with their highest orders of amplitude end up being:

$$O(\epsilon^0)Z_0 + O(\epsilon^1)Z_1 + O(\epsilon^2)Z_2 + O(\epsilon^3)Z_3 \quad [4]$$

Eq. 4 reveals that the stripe artifact contains not only the fundamental frequency k_1 determined by the unipolar gradient (Eq. 1), but also higher order harmonics with smaller amplitudes.

Strategies to suppress stripe artifact

While the EPG analysis revealed the presence of high order fluctuation in longitudinal magnetization after VS preparation (up to Z_3), only the harmonics that have spatial periods (hereafter denoted by λ_n) greater than twice the spatial resolution, will be captured in k-space data and visible in reconstructed images. While several design parameters affect the periods of the harmonics (as more detailed in Discussion section), a typical set of design parameters yields the area of unipolar gradient $> 5 \text{ mT}\cdot\text{msec}/\text{m}$ which corresponds to $k_1 > 0.21 \text{ mm}^{-1}$ and $\lambda_1 = k_1^{-1} < 4.8 \text{ mm}$. Assuming spatial resolution of 1 mm , k-space data will contain up to 2nd order harmonics at most since $\lambda_3 = \lambda_1/3 < 1.6 \text{ mm} < 2 \times \text{spatial resolution} = 2 \text{ mm}$.

As the EPG analysis reveals that the stripes can be approximated as superposition of two harmonics with periods of λ_1 and $\lambda_1/2$, we propose to alternately apply four VS preparation pulse trains which have excitation profiles are spatially shifted by 0 (original), $\lambda_1/2$, $\lambda_1/4$, and $3\lambda_1/4$, respectively; That is, each of the four preparation pulses is played separately every fourth cardiac cycle (which is therefore termed ‘four-cycle scheme’). The underlying rationale is that a portion of the spatial fluctuation made by each VS pulse is preserved until the next VS preparation due to incomplete M_z recovery so that the 4 phase-cycled spatial modulations affect the fluctuation amplitude in a destructive manner. With the original RF waveform denoted by $B_1(t)$, the RF waveform for a shifted excitation profile can be obtained by adding phase $\theta(t)$

$$B_1(t)e^{j\theta(t)}, \theta(t) = \gamma \int_t^T \Delta\lambda G(s)ds \quad [5]$$

where λ is the amount of the spatial shifting of excitation profile, T is the pulse duration, and $G(t)$ is the VS gradient waveform. Note that the four preparation pulses have the same excitation properties (e.g. flip angle, velocity selectivity) except different spatial responses.

The quality of stripe suppression will decrease with increasing M_z recovery between VS prepared acquisitions as the destructive contribution of the four pulses becomes sub-optimal.

For further suppression of the stripes, we note that the spatial fluctuation occurs only in the direction of the VS gradient (i.e. superior-to-inferior direction). With the frequency encoding (k_x) set to the S-I direction in this study, the stripe artifact will then manifest as impulses lying on the k -space line defined by $k_y = k_z = 0$. To further cancel out residual fluctuations with the two primary frequencies, we propose to acquire the k_x - k_y plane at $k_z = 0$ four times for the four VS preparations and to average the resultant 4 k_x - k_y data sets at $k_z = 0$. Since we cover each k_z partition by segmented acquisitions over 2 cardiac cycles, the scan time will be increased by $(4-1) \times 2 = 6$ cardiac cycles.

Numerical Simulation

Numerical simulations based on the Bloch equations were performed using Matlab (Mathworks, Natick, MA, USA) to confirm and assess stripe artifacts associated with VS preparation pulses in the presence of field errors. The design parameters for VS preparation included flip angle = 100° , five hard RF pulses, double refocusing using two 90° - 180° - 90° composite pulses, delay after unipolar gradient (T_d) = 0.5 ms, total pulse duration = 26.5 ms, and velocity pass-band = [7.0, 75.6] cm/s which was the same as the one for imaging the thigh in human subjects. Longitudinal magnetization for stationary tissues was simulated as a function of spatial position while each of the B_0 and B_1 offsets varied. The resultant spatial responses were 1D Fourier transformed to show their frequency responses.

Imaging Experiments

All experiments were performed on a 1.5 T whole-body MR scanner (Avanto; Siemens Medical Solutions, Erlangen, Germany) with 6-channel body matrix and spine receive coils. A bulk of chicken breast was scanned by VS-MRA pulse sequence which was triggered by emulated ECG signal, and consisted of a VS saturation pulse, a fat saturation pulse, and a segmented 3D bSSFP readout with centric view order. The VS preparation pulse was the same as the one used for the numerical simulation as well as subsequent human experiments; five hard RF pulses and double refocusing with two 90° - 180° - 90° composite pulses. The velocity pass-band of [7.8, 84.0] cm/s was the same as the one for imaging the thigh of a human subject. The corresponding fundamental frequency k_1 was 1.9 cm^{-1} . The chicken breast phantom was scanned (i) with the VS preparation pulse turned off, (ii) with one VS pulse (one-cycle scheme), (iii) with two alternate VS pulses spatially shifted by 0 and $\lambda_1/2$ (two-cycle scheme) (iv) with four alternate pulses shifted by 0, $\lambda_1/2$, $\lambda_1/4$, and $3\lambda_1/4$ (four-cycle scheme) and (v) with the averaging of the $k_z = 0$ plane in addition to the four-cycle scheme. Other imaging parameters were $1.2 \times 1.2 \times 1.4 \text{ mm}^3$, FOV = $24 \times 24 \times 4.4 \text{ cm}^3$, number of phase encodes per acquisition block = 50 and no parallel imaging reconstruction.

VS-MRA was performed in the calf ($n=1$) and the thigh ($n=2$) of healthy volunteers using the same VS preparation pulse as in the phantom experiment. The velocity pass-band designed for the calf was [4.7, 50.4] cm/s. For imaging the thigh, the pass-band was widened by 50 % (i.e., [7.0, 75.6] cm/s) by scaling down the VS gradient waveforms at the same rate. The imaging parameters were $1.1 \times 1.1 \times 1.2 \text{ mm}^3 / 1.1 \times 1.1 \times 1.4 \text{ mm}^3$ (calf/thigh), FOV = $36 \times 36 \times 96 \text{ cm}^3 / 36 \times 36 \times 134 \text{ cm}^3$, number of phase encodes per acquisition block = 52, 4-fold acceleration (net acceleration factor = 3.1 with 32 calibration lines) using self-consistent

parallel imaging reconstruction (SPIRiT) (20), and scan time = 2.3 min/2.7 min (calf/thigh) based on 70 beats/min. For each peripheral territory, two-cycle ($0 - \lambda_1/2$) and four-cycle ($0 - \lambda_1/2 - \lambda_1/4 - 3\lambda_1/4$) schemes were applied along with the averaging of the $k_z = 0$ plane.

Results

Computer-simulated stripes are represented as a function of B_0 offset in Fig. 2a and as a function of B_1 offset in Fig. 2d. The corresponding k-space signals are displayed over B_0 offset and B_1 scale in Figs. 2b and 2e, respectively. In k-space, the stripes appear as erroneous peaks at the locations of $k = k_1$ ($=1.9 \text{ cm}^{-1}$) and $2k_1$ ($=3.8 \text{ cm}^{-1}$), where k_1 is the fundamental frequency of the stripes calculated as Eq. 1 ($\gamma \int G_{\text{uni}}(t) dt$). Note that, with the spatial resolution of 1.2 mm assumed in the simulation, $2k_1$ corresponds to 92% of the maximum frequency (k_{max}) of 4.2 cm^{-1} ($= 1/0.12/2$). Over the tested ranges of B_0 offset ($-80 - 80 \text{ Hz}$) and B_1 scale ($0.8 - 1.2$), both the k_1 and $2k_1$ signals have maximum values on the orders of 10^{-2} relative to the DC component. Figs. 2c and 2f show example spectra yielded with B_0 offset of 30 Hz and off-resonance and B_1 scale of 0.9, respectively.

The result of scanning the chicken phantom is summarized in Fig. 3. The first through the third rows contain representative images, k_x - k_y planes at $k_z = 0$, and log-scaled k-space profiles along the dotted grey line, respectively for each of the five VS preparation schemes tested. The k-space profile was normalized by the value of k-space center (i.e. DC component) in each data set. The MR data obtained by applying the single-cycle preparation scheme yields stripe artifact in image domain (Fig. 3d) and erroneous peaks at the locations of $k_x = k_1$ ($=1.9 \text{ cm}^{-1}$) and $2k_1$ ($=3.8 \text{ cm}^{-1}$) in k-space (Figs. 3e and 3f), with good correlation with the simulation results. When the two-cycle preparation scheme was used, the peak at $k_x = k_1$ was significantly reduced but the $2k_1$ harmonics remained nearly the same (Figs. 3g, 3h and 3i). With the four-cycle scheme, the $2k_1$ harmonics were significantly reduced as well. The stripes are barely visible in the image domain (Fig. 3j), but the k-space peaks are still noticeable at $k_x = k_1$ and $k_x = 2k_1$ (Figs. 3k and 3l). With additional averaging of the k-space at $k_z = 0$, both the k_1 and $2k_1$ harmonics are further suppressed and no longer visible in both the image and k-space domains (Figs. 3m, 3n and 3o).

Figure 4 shows calf angiograms reformatted through maximum-intensity-projection, and the corresponding k-space data at $k_z = 0$. The angiogram obtained by using the single-cycle scheme shows stripes most severely near the bottom edge of the FOV presumably due to large B_0 and B_1 field offsets (Fig. 4a). The fundamental frequency k_1 was 2.9 cm^{-1} determined by the unipolar gradient (Eq 1) designed to yield the velocity passband of [4.7, 50.4] cm/s, and corresponded to 64% of the maximum k_x of 4.5 cm^{-1} with the spatial resolution of 1.1 mm used in this experiment (Fig. 4b). It should be noted that the stripes of $2k_1$ harmonic had higher frequency than 4.5 cm^{-1} and therefore was not captured during the data acquisition. When the two-cycle scheme was used, the stripes of k_1 harmonics were significantly reduced, as demonstrated in both the image and k-space domains (Figs. 4c and 4d). The stripe artifacts were well suppressed with the four-cycle scheme as well, with little difference in resultant angiograms and k-space data due to the absence of the $2k_1$ harmonics (Figs. 4e and 4f).

Figure 5 shows the results of VS-MRA in the thigh of a subject in the same format as in Fig. 4. Compared to calf MRA, the VS preparation pulse used in the thigh used smaller unipolar gradient (to widen the velocity passband) and therefore yielded lower fundamental frequency k_1 of 1.9 cm^{-1} . As a result, the obtained k-space data included not only the k_1 harmonics but the $2k_1$ harmonics that were 84% of the maximum k_x of 4.5 cm^{-1} (Fig. 5b). The two-cycle preparation scheme well suppressed the k_1 harmonics but barely affected the $2k_1$ harmonics, which resulted in reduced, but still noticeable stripe artifact. When the four-cycle scheme was used with the DC averaging, the stripes in image domain and the peaks at $k_x = 2k_1$ in k-space were further suppressed (Figs. 5e and 5f).

Discussion

It is quite natural to expect that the stripe artifact has a spatial frequency (termed k_1 in the present study) that corresponds to the rate of spins' dephasing generated by the unipolar gradient. This is true in the presence of single velocity excitation step which is equivalent to the flow-suppressed preparation pulses used in earlier studies (4–6). In this case, the stripes could be well suppressed by alternately using two $\lambda_1/2$ -cycled VS preparations pulses ($\lambda_1 = 1/k_1$). The EPG analysis in the present study has revealed, however, that consecutive application of multiple VS excitation steps results in higher-order harmonics as well. Since the maximum order of the harmonics included in k-space is likely two (i.e. $2k_1$ component) with typical spatial resolutions for angiography applications ($> 1 \text{ mm}$), four $\lambda_1/4$ -cycled VS preparations pulses were able to suppress the stripe artifact effectively.

The smaller the area of unipolar gradient, the more high-order harmonics have spatial frequencies lower than the given imaging resolution and therefore are visible in reconstructed images. Vascular territories with higher flow velocity require wider velocity pass-band and therefore need smaller unipolar gradient, increasing the chance for higher-order harmonics to be present in the stripes. Recall accordingly that thigh angiograms revealed both k_1 and $2k_1$ harmonics while calf angiograms used narrower velocity passband and showed k_1 component only. The number of refocusing pulses for each excitation step also has major effect on the size of unipolar gradient. Compared to the double-refocused design used in the present study, single-refocused design uses a smaller number of unipolar gradients and would need larger area of unipolar gradient to achieve the same velocity selectivity at the cost of increased sensitivity to field offsets. Another relevant design parameter is the delay period inserted after every unipolar gradient to reduce the eddy current effect. The longer the delay period, the smaller unipolar gradient is needed to yield the same first moment during each excitation step. These three parameters may happen to be set in a way that the stripe artifact includes higher harmonics than $2k_1$. For a somewhat extreme example, the combination of upper bound of velocity passband = 100 cm/s , number of refocusing pulses = 2, and post-unipolar delay = 1 ms results in k_1 of 1.1 cm^{-1} which will include 3 k_1 harmonics only if the imaging spatial resolution is smaller than 1.5 mm . In this case, as the proposed four phase-cycled preparations would not be able to suppress all the frequency components, it may be a practical solution to use spatial resolutions larger than the threshold value (1.5 mm).

The VS preparation pulse investigated in this study consists of five excitation segments and thus uses $(5-1) \cdot 2 = 8$ MLEV phase cycling steps with double refocusing scheme. In a recent study for cerebral applications (8,10), VS preparation pulses were designed with nine excitation segments along with 16 phase cycling steps, and appeared to yield negligible stripe artifacts. This reduction of stripe artifact is likely due to the increased number of phase cycling steps (from 8 to 16) which improves the immunity to B_1 offset. As the cerebral territories typically involve smaller B_1 variation and longer pulse duration increases T_2 relaxation and acceleration/deceleration effect (8,21), the number of excitation segments should be optimized under carefully designed protocols and analyses.

The main limitation of the presented study is in-vivo testing performed only in the calf and thigh of a limited number of subjects. The performance of the proposed scheme for stripe suppression may vary over subjects, depending mostly on the ranges of B_0 and B_1 field offsets. It may be more challenging to suppress the stripes in obese subjects (particularly in thigh and pelvis) or when either limb is positioned substantially off the iso-center (in the right-left direction). We have not tested the proposed approaches in pelvic regions to exclude the effect of respiratory motion. In fact, the respiratory motion itself may contribute to the formation of the stripes, and it would be worth to investigate the efficacy of the proposed schemes in the presence of motion.

In conclusion, extended phase graph analysis has shown that the stripe artifact associated with VS magnetization prepared MRA contains high-order harmonics as well as the fundamental frequency that is determined by each unipolar VS gradient. With approximation of the stripes as superposition of the first and second order harmonics, the artifact can be suppressed by alternate application of four VS preparation pulses whose excitation profiles are spatially shifted by quarter the fundamental period of the stripes. The suppression of the artifact can be further enhanced through additional k-space averaging with marginal increase in scan time.

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Fig. 1.

Top: Schematic diagram of velocity-selective excitation pulse sequence. Each velocity excitation step enclosed by two hard RF pulses (black bars), begins with a unipolar gradient, contains refocusing modules (dotted grey box), and ends with a unipolar gradient with the opposite polarity to the initial one. In the refocusing module, each of the two 180° rotations can be of various forms such as a single hard pulse and a composite pulse train. Note that additional delay period is used after each unipolar gradient to reduce eddy current effects.

Bottom: Extended phase graph analysis of spin ensemble states F_n and Z_n . The evolution of the ensemble states is described during the first excitation step by concatenating the effects of hard RF pulses, unipolar gradients and imperfect refocusing pulses which induce excitation of tiny flip angle ϵ . After ensemble states with amplitude orders lower than ϵ^3 are dropped, six longitudinal states are derived at the end of the pulse sequence, containing Z_1 , Z_2 , and Z_3 states.

Fig. 2.

Numerical simulations of stripe artifact induced by B_0 field variation (top row) and B_1 field variation (bottom row). a, d: The artifactual stripes start to appear when B_0 field or B_1 field deviate from the prescribed values. b, e: The stripes manifest as spurious peaks in k-space (displayed in log scale), specifically at two frequencies k_1 and $2k_1$ where k_1 is determined by the area of VS unipolar gradient (Eq. 1). Over the ranges of B_0 offset ($-80 - 80$ Hz) and B_1 scale ($0.8 - 1.2$), both the k_1 and $2k_1$ signals have maximum values on the orders of 10^{-2} relative to the DC component. c and f: Representative k-space profiles resulting from off-resonance of 30 Hz (c) and B_1 scale of 0.9 (f).

Fig. 3.

Results of scanning a bulk of chicken breast with different combinations of VS preparation pulses. Center slice images, k_x - k_y plane at $k_z=0$, and log-scaled profiles along the k_x axis (dotted line in b) are shown in the 1st, 2nd and 3rd rows, respectively. Single-cycle VS preparation scheme induced stripe artifacts (d) which appeared as spurious peaks at $k_x = k_1$ and $k_x = 2k_1$ (e and f). Two-cycle preparation scheme with $0 - \lambda_1/2$ shifting significantly reduced the k_1 harmonics but failed to reduce the $2k_1$ harmonic (g,h,i). Four-cycle preparation scheme with $0 - \lambda_1/2 - \lambda_1/4 - 3\lambda_1/4$ shifting significantly reduced both k_1 and $2k_1$ harmonics (j, k) which are however still noticeable in the log-scaled profile (l). Additional averaging of the k_x - k_y plane at $k_z = 0$, further suppressed the k_1 and $2k_1$ harmonics (m, n and o).

Fig. 4.

Partial maximum-intensity-projection (MIP) images (top row) and k-space data at $k_z = 0$ (bottom row) of VS-MRA in the calf. The unipolar gradient designed for the velocity-passband of $[4.7, 50.4]$ cm/s yielded the fundamental frequency k_1 of 2.9 cm^{-1} . This is large enough to make the 2nd order harmonics ($2k_1$) larger than the maximum k_x of 4.5 cm^{-1} determined by the spatial resolution of 1.1 mm. Due to the absence of the $2k_1$ harmonics, both the two-cycle and four-cycle preparation schemes well suppressed the stripe artifact.

Fig. 5.

Partial maximum-intensity-projection (MIP) images (top row) and k-space data at $k_z = 0$ (bottom row) of VS-MRA in the thigh. As the unipolar gradient designed for the velocity-passband of $[7.0, 75.6]$ cm/s yielded the fundamental frequency k_1 of 1.9 cm^{-1} , the $2 k_1$ harmonics (3.8 cm^{-1}) were also included in the k-space data that had the maximum k_x of 4.5 cm^{-1} determined by the spatial resolution of 1.1 mm (b). While the two-cycle preparations scheme suppressed only the k_1 harmonics (c, d), the four-cycle preparation scheme could suppress both the k_1 and $2 k_1$ harmonics (e, f), which coincides with the result of the chicken phantom experiment.