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Non-Contrast SSFP Pulmonary Vein MRA: Impact of Off-Resonance and Flow

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Abstract

Purpose—To investigate pulmonary vein (PV) off-resonance and blood flow as causes of signal void artifacts in non-contrast steady-state-free-precession (SSFP) PV MR angiography (MRA).

Materials and Methods—PV blood off-resonance was measured on 11 healthy adult subjects and 10 atrial fibrillation (AF) patients. Non-contrast PV MRA was performed using a three-dimensional slab-selective SSFP sequence at 1.5T on 7 healthy subjects with signal profile shifts of 0-125Hz. The time-resolved blood flow velocity of the PVs was measured on 5 healthy subjects. The impact of flow was studied on 6 healthy subjects, on whom SSFP PV MRA was acquired twice with the ECG trigger delay corresponding to low and high flow, respectively.

Results—The PV off-resonance were 97 ± 27 Hz, 65 ± 20 Hz, 74 ± 25 Hz, and 52 ± 17 Hz for right inferior, left inferior, right superior and left superior PVs, respectively, on healthy subjects, and were 74 ± 20 Hz, 38 ± 9 Hz, 51 ± 20 Hz, and 28 ± 11 Hz on AF patients ($P < 0.01$ for all). The off-resonance caused severe signal voids in the PVs. Signal acquired during mid-diastole with high PV flow caused additional signal voids in the left atrium, which was reduced by setting the ECG trigger delay to late-diastole.

Conclusion—PV off-resonance and flow causes signal void artifacts in non-contrast three-dimensional slab-selective SSFP PV MRA.

Keywords

Pulmonary vein angiography; off-resonance; atrial fibrillation; SSFP; non-contrast

INTRODUCTION

Atrial fibrillation (AF) is the most common sustained arrhythmia, afflicting over 2.2 million Americans (1). PV isolation (PVI) using radiofrequency (RF) ablation has become an accepted option for AF treatment (2). Imaging is commonly performed prior to PVI to assess the anatomic features of the PVs and the left atrium (LA) as well as the anatomic relationship between the LA and the esophagus and adjacent vascular structures (3). Imaging

is often performed post-PVI for detection of post-procedural complications such as PV stenosis (4).

PV images are commonly acquired with magnetic resonance (MR) or multi-detector computed tomography (MDCT). Contrast-enhanced MR angiography (MRA) is the preferred imaging modality due to lack of ionizing radiation exposure and iodinated contrast agents for a procedure that usually requires repeated imaging due to AF recurrence. In current clinical practice, contrast-enhanced PV MRA is typically acquired during a prolonged breath-hold and the first-passage injection of gadolinium-based contrast agents without any cardiac gating (5). A non-ECG-gated acquisition results in image blurring and over-estimation of PV size (6). In addition, there are adverse safety implications of gadolinium contrast agents for patients with impaired renal function (7).

Non-contrast, three-dimensional (3D), free-breathing balanced steady state free precession (SSFP) methods have been used for imaging the coronary (8) and renal arteries (9). SSFP based imaging sequences have been recently reported for non-contrast PV MRA (10-12). In these methods, a non-selective excitation and a short repetition time (TR) allows acquisition of PV MRA, but with the necessity of imaging in coronal orientation with large field of view (FOV) to avoid fold-over artifacts (10,11), which prolongs the imaging time.

In our experience, signal voids in the PVs and the LA are often observed in high spatial-resolution non-contrast SSFP acquisitions; however the source of this artifact is not yet known. There are two potential causes for these signal void artifacts: 1) PV off-resonance and/or 2) PV blood flow. PVs are in close proximity to the lungs, which are sources of strong changes in resonance frequency. These magnetizations corresponding to these frequency shifts may be severely suppressed in SSFP imaging, resulting in signal voids or banding artifacts (13). Blood flow in the presence of off-resonance is also a potential source of artifacts in SSFP imaging (14).

In this study, we sought to investigate the potential sources of signal void artifacts in non-contrast PV MRA in both healthy adult subjects and a cohort of AF patients.

MATERIALS AND METHODS

Our study was performed on a 1.5T system (Achieva, Philips Healthcare, Best, Netherlands) with a five-element cardiac phased-array receiver coil. Written informed consent was obtained from all subjects and the protocol was approved by our Committee on Clinical Investigations.

Impact of Off-Resonance

PV Off-Resonance Measurements—A multi-slice, ECG-gated two dimensional (2D) gradient recalled echo (GRE) based sequence was used to measure cardiac phased-resolved B_0 field maps of the PV and LA (15-17). For each slice, two separate images were collected with identical imaging parameters except at two different TEs and the phase accrued between the two was used to calculate the B_0 field map according to the following equation:

$$f = \frac{\phi}{2\pi\Delta TE},$$

where f is the off-resonance frequency, ΔTE is TE difference between two acquisitions (2 ms) and ϕ is the phase accrual during the period of ΔTE .

To quantify the PV blood frequency off-set, we recruited 11 healthy adult subjects (age = 22 ± 2 years, 5 male) and 10 AF patients (age = 58 ± 10 years, 6 male) who were referred to PV MRA prior to or after PVI. Cardiac phased-resolved B_0 field maps were acquired with 3 averages during free breathing without other means of respiratory compensation (image parameters: $TE/TR/\alpha = 2.1/5.8 \text{ ms}/10^\circ$ $TE_1 = 2.1 \text{ ms}$, $TE_2 = 4.1 \text{ ms}$, $FOV = 400 \times 320 \text{ mm}^2$, spatial resolution of $2 \times 2 \text{ mm}^2$ reconstructed to $1.25 \times 1.25 \text{ mm}^2$, typical temporal resolution of 100 ms, 8 mm slice thickness, and 5-7 slices). All images were reconstructed on the imaging console.

PV Imaging—To demonstrate the effect of the PV off-resonance on SSFP PV MRA, a 3D free-breathing ECG-triggered SSFP sequence, prescribed axially covering LA and all PVs, was used for non-contrast PV MRA on 7 healthy adult subjects (21 ± 2 years, 4 male). The PV MRA was repeated with shifted SSFP signal profile up to 125Hz in increments of 25Hz by applying a linear RF phase ramp in the SSFP excitation pulses corresponding to the frequency shifts. The typical imaging parameters were: $TR/TE/\alpha = 3.8/1.9 \text{ ms}/90^\circ$, 35 phase encoding lines per heartbeat, $FOV = 320 \times 400 \times 60 \text{ mm}^3$, isotropic spatial resolution of $1.8 \times 1.8 \times 1.8 \text{ mm}^3$ reconstructed to $0.9 \times 0.9 \times 0.9 \text{ mm}^3$. Automatic volumetric shimming, covering the LA and PVs, was used for our PV imaging study. A navigator echo was prescribed on the dome of the right hemidiaphragm with a 7-mm acceptance window to compensate for respiratory motion. An adiabatic T_2 -prep pulse with 50-ms TE was used to suppress myocardium signal (18). To reduce the effect of PV off-resonance on SSFP signal, the steady-state catalyzation sequence proposed by Foxall et al. (19), which is more effective for catalyzing the steady state for off-resonance spins compared to conventional $\alpha/2$ preparation sequence (20), was used before each imaging shot. The catalyzation sequence included a longitudinal magnetization preparation ($\beta = 15^\circ$) followed by 10 excitation pulses with linearly ramping up flip angles. The typical imaging time was ~5 min without parallel imaging.

Data Analysis—To measure off-resonance of PV and LA blood, region of interest (ROI) was drawn in the proximal PVs and LA cavity in the off-resonance field maps and the mean off-resonance frequency was recorded throughout the cardiac cycle for the right inferior PV (RIPV), right superior PV (RSPV), left inferior PV (LIPV) and left superior PV (LSPV).

A linear mixed-effects model with compound symmetry variance-covariance structure for the error matrix (21) was used for analysis of the PV off-resonance for both AF patient and healthy subjects. A two-tailed P value < 0.05 was considered to indicate significance. All statistical analysis was performed in SAS (version 8.01, SAS Institute, Cary, NC).

Impact of PV Blood Flow

PV Blood Flow Measurements—A two-dimensional (2D) free-breathing cine phase contrast GRE sequence, prescribed as two sagittal slices on both sides of the heart, was used to measure the time-resolved blood flow velocity in left and right PVs on 5 healthy subjects (25 ± 6 years, 2 male). The imaging parameters were: $TR/TE = 5.0/3.0 \text{ ms}$, $FOV = 320 \times 260 \text{ mm}^2$, spatial resolution $2.5 \times 2.5 \text{ mm}^2$ reconstructed to $1.25 \times 1.25 \text{ mm}^2$, slice thickness 8 mm, and maximum encoding velocity 100 cm/s.

PV Imaging—The PV blood flow may impact the choice of ECG trigger delay time to minimize PV flow. To study this effect, PV MRA was performed on 6 healthy adult subjects (28 ± 8 years, 2 male) using the 3D SSFP PV MRA sequence without frequency shift in signal profile. The imaging parameters were the same as in the previously described PV imaging study of the impact of off-resonance. The acquisition was repeated using two ECG

trigger delays of mid vs. late diastole corresponding to high and low PV blood flow, respectively.

Data Analysis—An ROI on the cross-section of each major PV was selected on the magnitude image and its location was copied into the phase velocity map. The time-resolved PV flow velocity, measured on scanner console, was imported to Matlab (MathWorks, Natick, MA), where the PV flow curves were normalized to cardiac cycle and the mean and standard deviation between all subjects were calculated.

RESULTS

Impact of PV Off-Resonance

Figure 1 shows an example of PV magnitude image and corresponding resonance frequency field map in a healthy adult subject at four different times within the cardiac cycle. A frequency shift of ~100 Hz can be seen in the proximal RIPV throughout the cardiac cycle whereas the blood pool in the LA is on-resonance. Figures 2 and 3 show the PV off-resonance for healthy subjects and AF patients, respectively. The PV off-resonance frequencies (averaged through the cardiac cycle and using the LA frequency as reference) were 97 ± 27 Hz, 65 ± 20 Hz, 74 ± 25 Hz, and 52 ± 17 Hz for RIPV, LIPV, RSPV and LSPV, respectively, on healthy subjects ($P < 0.01$ for all PVs). Off-resonance of 74 ± 20 Hz, 38 ± 9 Hz, 51 ± 20 Hz, and 28 ± 11 Hz for RIPV, LIPV, RSPV and LSPV, respectively, was seen on AF patients ($P < 0.01$ for all PVs). The off-resonance remains relatively constant through the cardiac cycle for all PVs for both healthy and AF patients ($P > 0.9$ for both healthy subjects and AF patients). The off-resonance of RIPV was significantly higher than other PVs ($P < 0.01$ for both healthy subjects and AF patients). The PV off-resonance of AF patients were significantly lower than healthy subjects ($P < 0.01$ for all PVs).

In conventional SSFP acquisitions, without shifts in SSFP signal profile, the PV signal was severely suppressed. In the SSFP acquisitions with shifted signal profile of 25-50 Hz, the PV signal voids were reduced. With a shift of 75-125 Hz, the signal intensity of the PVs was greatly enhanced while the on-resonance structures such as the LA were suppressed (images corresponding to 0-125 Hz shifted signal profiles not shown). Figure 4 shows four different slices from the 3D PV MRA dataset, each at the levels of RIPV, LIPV, RSPV, and LSPV. Images in the top row were acquired using a 0° - 180° RF phase alternation, which excites the on-resonance spins. The bottom row was acquired using an additional linear excitation RF phase ramp of 75 Hz along successive RF excitation pulses, corresponding to a frequency shift of 75 Hz in the signal profile of SSFP. The PV branches suffer from signal void in the images acquired with an on-resonance excitation (top row), while they can be seen with a shifted SSFP frequency profile. This further confirms our previous observation of the PV frequency shift and its impact on non-contrast PV MRI.

Impact of PV Flow

The mean and standard deviation of the blood flow velocity within the cardiac cycle for each PV for 5 subjects is shown in Figure 5. The maximum blood velocity was 30-35 cm/s through the cardiac cycle with minimal negative flow (-8 - 0 cm/s) during late diastole (after atrial contraction). Flow velocity pattern of all PVs were similar and consisted of 3 waveforms of high velocity S wave (peak velocity: 30 ± 3 cm/s for LIPV, 36 ± 12 cm/s for LSPV, 35 ± 4 cm/s for RIPV, and 31 ± 8 cm/s for RSPV) in ventricular systole, high velocity D wave (23 ± 11 cm/s for LIPV, 24 ± 10 cm/s for LSPV, 27 ± 11 cm/s for RIPV, and 24 ± 10 cm/s for RSPV) in early diastole, and low negative/reversal velocity wave (6.8 ± 1.6 cm/s for LIPV, 8.0 ± 1.9 cm/s for LSPV, 8.3 ± 1.8 cm/s for RIPV, and 6.4 ± 1.6 cm/s for RSPV) in late diastole due to atrial contraction (22). Of the six 3D SSFP PV images acquired, additional

signal voids were observed in PVs and LA in four subjects when PV MRA was acquired during late diastole compared to mid diastole (Figure 6). Signal voids are seen in both PV and LA with high severity in mid-diastolic acquisition, whereas in the late diastole acquisition, the signal void in the LA was eliminated. This suggests that to reduce flow related artifacts, non-contrast PV MRA should be acquired during late diastole, corresponding to the low PV flow period between the D wave and the atrial reversal wave.

DISCUSSION

In this study, we investigated the causes of the often seen signal void artifacts in non-contrast SSFP PV MRA. We demonstrated for the first time the presence of significant temporally constant off-resonance in the PV blood in both healthy subjects and AF patients. This off-resonance causes severe signal voids in the PVs. In addition, PV blood flow, in combination with the PV off-resonance, causes additional signal void artifacts that are sometimes seen in the LA, which can be mitigated by adjusting the ECG trigger delay time to late diastole corresponding to low PV flow.

As the off-resonance of the PV and LA are measured while the spins are flowing, there is a potential impact of blood flow on the off-resonance measurements, as flowing spins may cause phase shift in addition to B0 field inhomogeneity. However, the impact of flow on our off-resonance measurements should be minimal because the phase shift was calculated based on two separate acquisitions with two TEs. Therefore, the flowing spins should accumulate similar phase in the two acquisitions, which is subsequently canceled during the phase subtraction.

The SSFP sequence used in this study is structurally analogous to 3D coronary MRI sequences (8,23), but with lower spatial resolution. Recent reports on non-contrast SSFP PV MRA (10-12) used non-selective RF pulses, high receiver bandwidth, and partial echo to shorten TR and increase SSFP pass-band width. Consequently, imaging has to be performed in the coronal plane with an FOV in the slice-encoding direction of 150-250 mm to prevent aliasing. Therefore, the SSFP sequence used in this study with a 60-80 mm axial imaging slab and a selective excitation RF pulse may be a promising alternative approach with shortened imaging time. The PV and LA signal voids described in this study has not been reported in previous investigations (10-12). We speculate the short TR (~2.5ms) enabled by non-selective RF pulses may be a reason for the absence of signal voids in these previous studies. A direct comparison between our axial slab-selective approach with the previously reported coronal non-selective approach is needed to further identify the benefits and drawbacks of each method.

In the examples showed in Figure 4, the off-resonance SSFP highlighted the PV signal but suppressed the on-resonance LA signal, which is also of interest for the PV isolation procedure. Several previously proposed methods for compensating for SSFP banding artifacts using combination of two SSFP acquisitions with different radiofrequency phase cycling (24-26) or wideband SSFP (27) may be used to reduce signal voids in the PV while maintaining a high signal from the LA.

The RIPV has significantly higher off-resonance than the other PVs on both healthy subjects and AF patients. Although we could not give a definitive explanation, we speculate the difference may be attributed to the difference in the morphology of the right and left lungs and the distance between the lungs and the PVs.

In light of the PV off-resonance, an alternative approach to non-contrast PV MRA is to use gradient recalled echo (GRE) sequences (28). Based on our initial experience, the impact of PV off-resonance on non-contrast GRE PV MRA at 1.5T is minimal as GRE is less sensitive

to off-resonance. With the increased use of 3T systems, we expect more severe PV off-resonance at 3T. Therefore, the implication of the described PV off-resonance at 3T on both SSFP and GRE non-contrast PV MRA needs to be further studied.

Another potential source of artifacts is the use of navigators in the free-breathing SSFP sequence. The pencil-beam navigators placed on the right hemidiaphragm could generate some interference in the right PV signal. However, it is unlikely the major cause of the signal voids that we observed in the SSFP PV MRA images because the signal voids were also observed in the left PVs.

Our results indicate the PV off-resonance in AF patients is significantly lower than healthy subjects. However, it is large enough to cause the described signal void artifacts and should be considered when using SSFP for PV MRA. We note that the AF patients and healthy subjects for off-resonance measurements were not matched for age or gender, which is a limitation of our study.

In conclusion, off-resonance and flow can cause signal void artifacts in slab-selective 3D SSFP PV MRA. The artifacts can be reduced by shifting the frequency of SSFP signal profile and adjusting the ECG trigger delay.

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Figure 1.

Right inferior pulmonary vein (RIPV) frequency shift in a healthy adult subject during the cardiac cycle. Significant frequency shift ($\sim 100\text{Hz}$) can be seen in the RIPV throughout the cardiac cycle, while the adjacent left atrium (LA) blood pool shows no such frequency offset. The time point during the cardiac cycle is labeled for each image. TD=trigger delay.

Figure 2.

Time resolved PV off-resonance in healthy subjects. There is significant off-resonance in all PVs ($P < 0.01$ for all PVs). There is significantly higher off-resonance in RIPV compared with the other PVs ($P < 0.01$ for all). The off-resonance is constant throughout cardiac cycle and the effect of time during cardiac cycle on PV off-resonance is non-significant ($P > 0.9$). LIPV: left inferior PV; RSPV: right superior PV; LSPV: left superior PV.

Figure 3.

Time resolved PV off-resonance in AF patients. Similar to results show in Fig. 2, there is significant PV off-resonance in atrial fibrillation (AF) patients in all PVs ($P < 0.01$ for all PVs), which does not significantly change with time during cardiac cycle ($P > 0.9$ for all PVs). The PV off-resonance of AF patients were significantly lower than healthy subjects ($P < 0.01$ for all PVs).

Figure 4.

Four example slices (A-D) of non-contrast PV MRI using 3D SSFP reconstructed from a data set acquired with on-resonance (top row), and 75Hz off-resonance (bottom row) SSFP radiofrequency phase-cycling schemes, demonstrating the impact of PV off-resonance on SSFP PV MRA. Signal loss in the RIPV, RSPV, LIPV, and LSPV is observed in the on-resonance images due to PV off-resonance. The PV off-resonance for this example: RIPV (101Hz), RSPV (85Hz), LIPV (65Hz), and LSPV (56Hz).

Figure 5.

Blood flow velocity in the LIPV, LSPV, RIPV and RSPV during the cardiac cycle derived from five healthy subjects. High PV blood velocity is observed during most of the cardiac cycle with reversal of flow during late diastole (after atrial contraction). S: systolic wave. D: diastolic wave. AR: atrial reversal wave.

Figure 6.
Example of PV images acquired in a healthy subject during a) low and b) high PV flow. High PV blood flow causes additional signal voids in the LA (arrow). TD: ECG trigger delay (in ms)