Magnetic Resonance Imaging 53 (2018) 82–88

Contents lists available at ScienceDirect

Magnetic Resonance Imaging

journal homepage: www.elsevier.com/locate/mri

Frequency-modulated bSSFP for phase-sensitive separation of water and fat

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ARTICLE INFO

Keywords:
Acquisition methods
Water fat imaging
Post-acquisition processing
bSSFP
Frequency-modulation

ABSTRACT

Our study proposes the use of a frequency-modulated acquisition which suppresses banding artefacts in combination with a phase-sensitive water-fat separation algorithm.

The performance of the phase-sensitive separation for standard bSSFP, complex sum combination thereof, and frequency-modulated bSSFP were compared in in vivo measurements of the upper and lower legs at 1.5 and 3 T. It is shown, that the standard acquisition suffered from banding artefacts and major swaps between tissues. The dual-acquisition bSSFP could alleviate banding artefacts and only minor swaps occurred, but it comes at the expense of a doubled acquisition. In the frequency-modulated acquisitions all banding artefacts and the associated phase jumps were eliminated and no swaps between tissues occurred. It therefore provides a means to robustly separate water and fat, in one single radial bSSFP scan, using the phase-sensitive approach, even in the presence of high field inhomogeneities.

1. Introduction

The separation of signal originating from water and fat is of high clinical relevance. In many MRI sequences fat produces very bright signal, which can itself be of interest, but more often overlays the diagnostically interesting information from water [1]. Many different approaches were reported, starting from suppression of fat during the excitation to complex post-processing strategies [1–3].

Recently, the characteristics of balanced steady state free precession (bSSFP) sequences were exploited to enable a separation. Commonly used in cardiac applications, the high signal-to-noise-ratio (SNR) and very short scan times are desirable for water-fat imaging as well. It has been shown, that bSSFP can be combined with all general fat suppression or separation techniques, like magnetization preparation [4,5], multi-echo [6] and complex sum bSSFP [7] approaches. Additionally, the special signal behavior in itself and high sensitivity towards off-resonance proved to be useful for water-fat separation [8–10].

The signal varies periodically between regions of high signal, also called passbands, and signal nulls, which are accompanied by a phase jump. A difference Δf between the RF synthesizer and local precession frequency, causes a dephasing θ in the signal within one TR: $\theta = 2\pi * \Delta f * TR$ [11]. Wherever the dephasing amounts to $\theta = \pi \pm n * 2\pi$, in a standard bSSFP experiment the signal nulls appear as visible banding artefacts in the image.

The phase-sensitive water-fat separation approach exploits the difference in precession frequency between water and fat and the resulting difference in signal phase [12–14]. To create a phase difference of π between water and fat, measurement parameters need to be chosen such that water and fat signal are located an odd number of signal pass bands apart. This is achieved by choosing TR as the reciprocal of the chemical shift between the two tissues (or an odd multiple thereof): $TR = n/(f_{water} - f_{fat})$, where n is an odd integer. Assuming the chemical shift between water and the main peak of fat to be 3.5 ppm, the lowest possible TR values are 4.6 ms for 1.5T or 2.4 ms for 3T. In the resulting image, the phase information can now be used to separate pixels containing mainly water from pixels containing mainly fat.

Unfortunately, such a phase change can also be caused by field inhomogeneity. Especially, in areas with highly uneven field, like close to implants or interfaces, the off-resonance can change considerably, which can ultimately cause a phase jump within one and the same tissue. The resulting false identification of some areas can be seen as swaps in water- or fat-only images [14,15]. One approach to solve for these swaps is the acquisition of multiple phase-cycled bSSFP images and their combination in order to smooth the image phase [13]. Unfortunately, the acquisition of multiple images always prolongs measurement time and increases the vulnerability to motion artefacts.

A different approach for banding free imaging is frequency-

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https://doi.org/10.1016/j.mri.2018.06.005
Received 5 December 2017; Received in revised form 27 April 2018; Accepted 10 June 2018

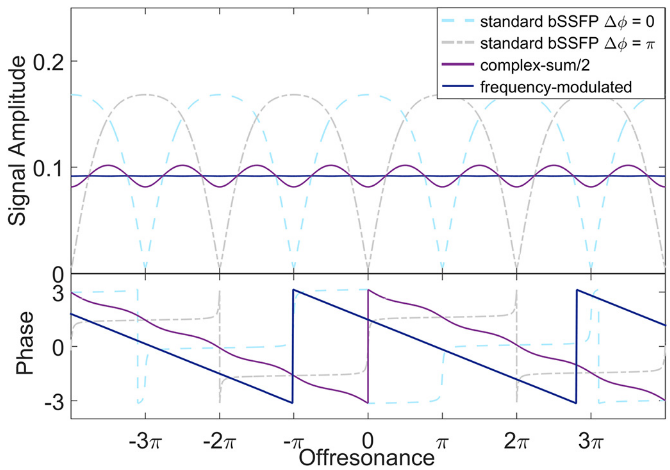

Fig. 1. Off-resonance profile for two phase-cycled standard bSSFP acquisition (dashed gray/light blue) and one frequency-modulated bSSFP acquisition (dark blue). Dual acquisition (violet) describes the complex sum of the two phase-cycled acquisitions. The intensity was normalized by the number of phase-cycled acquisition (2 in this case) to be comparable. The signal voids and phase jumps lead to the typical banding artefacts in standard bSSFP, while the magnitude and phase behavior of the complex sum combination and frequency-modulated bSSFP are smooth. Simulation parameters: T1 = 800 ms, T2 = 100 ms, TR = 4 ms, TR = 2 ms, flipangle = 80°. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

modulation [16–18]. It has been reported, that the steady state of bSSFP tolerates small changes in frequency [16] which allows to constantly change the measurement frequency during the acquisition and therefore to collect different lines in k-space with different off-resonance values. For practical reasons, this frequency modulation can also be realized as a phase shift in the RF-pulses to avoid slice shifts. Calculations [16] and experiments [17] establish an upper limit of about 1° of phase change in one step for the frequency-modulated experiment to provide satisfactory signal levels.

In combination with a radial acquisition [17, 18], the gridding process during reconstruction combines the information from different spokes with different off-resonances in one single k-space. The resulting signal behavior is therefore comparable to the complex sum combination of multiple phase-cycled acquisitions. Exemplary signal behavior for two phase-cycled acquisitions, their combination as a complex sum (dual-acquisition) and frequency-modulated bSSFP is shown in Fig. 1. The complex sum signal is expected to show less rippling with an increasing number of combined images [13,19].

In a frequency-modulated acquisition the signal is sampled from as many different off-resonance positions as there are acquired lines. Therefore, it should be noted that the signal behavior, and especially phase behavior, of frequency-modulated bSSFP is similar to the behavior of the complex sum signal for a high number of phase-cycled acquisitions. One drawback of the single frequency-modulated acquisition is overall lower signal intensity due to destructive interference of signal, featuring different phases, during the gridding operation. A multi-frequency reconstruction was proposed as possible remedy [20].

The linear phase off-resonance profile, achieved using frequency-modulated bSSFP, lends itself to the phase-sensitive reconstruction methods proposed in [13]. In this work, we apply the phase-sensitive fat-water technique described in [13] to a single frequency-modulated radial bSSFP acquisition [16, 17] using the multifrequency reconstruction proposed in [20] to achieve simultaneous band-reduction/elimination and robust fat/water separation in an SNR-efficient manner. We demonstrate the technique in vivo in the lower legs of volunteers at both 1.5T and 3T.

2. Methods

2.1. Measurements

All in vivo measurements were approved by the local ethics committee and comply with the regulations of the Declaration of Helsinki. Informed consent was obtained from all volunteers before scanning.

Standard bSSFP and frequency-modulated measurements were performed using the same preparation, setting and trajectory, resulting in identical measurement times for each scan. For 2D acquisitions a golden angle radial trajectory was used. For the acquisition of 3D volumes a stack of stars trajectory was used, featuring golden angle increments between radial spokes within one star and a small angle offset between the stars in different partitions [21].

The frequency-modulation was set up such that one period in the off-resonance profile was covered during one acquisition. More precisely, to cover 360° the phase shift between two consecutive pulses was $\Delta\theta = 360^{\circ}/nl$, where nl is the total number of lines acquired.

To test the performance of the water fat separation algorithm for worst case scenarios, the linear shim value was detuned, to provoke banding artefacts, in the head/foot or left/right-direction for 3D and 2D acquisitions respectively.

2.1.1. Acquisitions at 1.5T

The lower legs of a healthy volunteer were scanned in a 1.5T MR system (MAGNETOM Aera, Siemens Erlangen, Germany). One frequency-modulated bSSFP and two phase-cycled standard bSSFP acquisitions were performed. All datasets were acquired using a golden angle stack-of-stars trajectory with 128 slices per slab and 526 projections each. Further parameters were: TR = 4.6 ms, TE = 2.3 ms, flip angle = 30°, bandwidth = 434 Hz/Px, spatial resolution = 1 × 1 × 1 mm^3, FOV = 320 × 320 × 128 mm^3. For frequency-modulation a phase shift of 0.0053° was employed. A field gradient, estimated to be about 30 μT/m was applied using a linear shim offset. The total acquisition time was 5 min 55 s for frequency-modulated bSSFP and each of the two phase-cycled acquisitions.

A cross section of the lower leg of a healthy volunteer was scanned in the same MR system. Here, one frequency-modulated bSSFP measurement and one standard bSSFP acquisitions were performed for TR values of 4.6 ms, 13.8 ms and 23 ms. Datasets were acquired using a 2D golden angle radial trajectory with 1000 spokes (TE = TR/2, flip angle = 70°, bandwidth = 674 Hz/Px, spatial resolution = 0.7 × 0.7 mm^2, FOV = 340 × 340 mm^2). For frequency-modulation a phase shift of 0.63° was employed. A field gradient, estimated to be about 40 μT/m was applied using a linear shim offset. Total acquisition times were 7 s, 21 s and 35 s for the different TR values.

Additionally, a phantom consisting of bacon and a metal hip prosthesis was scanned in the same scanner. One frequency-modulated bSSFP measurement and two phase-cycled standard bSSFP acquisitions were performed using the golden angle stack-of-stars trajectory with 32 slices per slab and 420 projections each. Further parameters were: TR = 4.6 ms, TE = 2.3 ms, flip angle = 40°, bandwidth = 673 Hz/Px, spatial resolution = 1 × 1 × 1 mm^3, FOV = 250 × 250 × 32 mm^3. For frequency-modulation a phase shift of 0.0214° was employed. Here, the area within the FOV was carefully shimmed as in standard protocols. The total acquisition time was 1 min 21 s for frequency-modulated bSSFP and each of the two phase-cycled acquisitions.

2.1.2. Acquisitions at 3T

The lower leg of a healthy volunteer was scanned in a 3T MR system (MAGNETOM Skyra, Siemens Erlangen, Germany). Here, one frequency-modulated bSSFP measurement and one standard bSSFP acquisitions were performed for a TR value of 7.2 ms. All datasets were acquired using a radial golden angle stack-of-stars trajectory with 96 slices per slab and 592 projections each (TE = TR/2, flip angle = 30°, bandwidth = 220 Hz/Px, spatial resolution = 1.1 × 1.1 × 1.1 mm^3,