Fast isotropic banding-free bSSFP imaging using 3D dynamically phase-cycled radial bSSFP (3D DYPR-SSFP)

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Abstract

Aims: *Dynamically phase-cycled radial balanced steady-state free precession (DYPR-SSFP) is a method for efficient banding artifact removal in bSSFP imaging. Based on a varying radiofrequency (RF) phase-increment in combination with a radial trajectory, DYPR-SSFP allows obtaining a banding-free image out of a single acquired k-space. The purpose of this work is to present an extension of this technique, enabling fast three-dimensional isotropic banding-free bSSFP imaging.*

Methods: *While banding artifact removal with DYPR-SSFP relies on the applied dynamic phase-cycle, this aspect can lead to artifacts, at least when the number of acquired projections lies below a certain limit. However, by using a 3D radial trajectory with quasi-random view ordering for image acquisition, this problem is intrinsically solved, enabling 3D DYPR-SSFP imaging at or even below the Nyquist criterion. The approach is validated for brain and knee imaging at 3 Tesla.*

Results: *Volumetric, banding-free images were obtained in clinically acceptable scan times with an isotropic resolution up to 0.56 mm.*

Conclusion: *The combination of DYPR-SSFP with a 3D radial trajectory allows banding-free isotropic volumetric bSSFP imaging with no expense of scan time. Therefore, this is a promising candidate for clinical applications*

Schnelle isotrope bandingfreie bSSFP-Bildgebung mit 3D dynamisch phasenzykliertem radialem bSSFP (3D DYPR-SSFP)

Zusammenfassung

Ziele: *Dynamisch phasenzykliertes radiales bSSFP (DYPR-SSFP) stellt eine Methode zur effizienten Entfernung von Bandingartefakten bei der bSSFP-Bildgebung dar. Basierend auf einem sich ändernden Phaseninkrement der Hochfrequenz(HF)-Pulse sowie einer radialen Trajektorie kann mittels DYPR-SSFP ein bandingfreies Bild aus einem einzelnen akquirierten k-Raum gewonnen werden. Das Ziel dieser Arbeit ist die Weiterentwicklung der besagten Technik, wodurch schnelle dreidimensionale isotrope bandingfreie bSSFP-Bildgebung ermöglicht wird.*

Methoden: *Die Entfernung von Bandingartefakten mit DYPR-SSFP basiert auf der Verwendung eines dynamischen Phasenzyklus, was bei der Unterschreitung einer gewissen Anzahl von akquirierten Projektionen zu Artefakten führen kann. Die Verwendung einer 3D-radialen Trajektorie mit einer quasizufälligen Anordnung löst dieses Problem und erlaubt 3D DYPR-SSFP-Bildgebung, bei der das Nyquist-Kriterium gerade erfüllt oder sogar unterschritten wird. Validiert wird dieser Ansatz mittels Gehirn- sowie Kniemessungen bei 3 Tesla.*

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such as imaging of cranial nerves or articular cartilage.

Keywords: Radial imaging, SSFP sequences, 3D isotropic, banding removal

Ergebnisse: *Es konnten volumetrische, bandingfreie Bilder in klinisch akzeptablen Messzeiten mit einer isotropen Auflösung von bis zu 0,56 mm erzielt werden.*

Schlussfolgerungen: *Die Kombination von DYPR-SSFP mit einer 3D-radialen Trajektorie erlaubt bandingfreie isotrope volumetrische bSSFP-Bildgebung ohne zusätzliche Erhöhung der Messzeit. Folglich ist die vorgestellte Technik ein vielversprechender Kandidat für klinische Anwendungen wie beispielsweise die Bildgebung von Gehirnnerven oder Gelenkknorpel.*

Schlüsselwörter: Radiale Bildgebung, SSFP-Sequenzen, 3D-isotrop, Entfernung von Bandingartefakten

Introduction

Balanced steady-state free precession (bSSFP) sequences are able to generate images with high signal-to-noise ratio (SNR) and excellent fluid-tissue contrast in very short scan times [1]. Besides cardiac imaging [2], typical applications are imaging of the musculoskeletal system [3] and the depiction of cranial nerves [4,5].

However, one of the major drawbacks of bSSFP is its high sensitivity to off-resonances originating from magnetic field inhomogeneities. These off-resonances manifest as banding artifacts throughout the image and can render images non-diagnostic, thereby considerably limiting the value of bSSFP. Well-known countermeasures are the use of short repetition times (TR) [1,6] in order to increase the spectral distance between signal voids or the acquisition of several phase-cycled images [7–13] in order to place the artifacts at different spatial locations and to suppress them by subsequent signal processing. While the former approach is limited by hardware constraints and only produces banding-free images for rather low inhomogeneities and moderate field strengths, the latter approach is more robust in terms of banding removal. However, the acquisition of multiple images with different radiofrequency (RF) phase-increments (phase-cycles) between subsequent TRs can be hindered by long scan times.

Recently, a novel technique for banding-free bSSFP imaging has been proposed, called dynamically phase-cycled radial bSSFP (DYPR-SSFP) [14]. The basic principle of DYPR-SSFP is to combine a dynamically changing phase-increment with a (quasi-) randomly sampled radial trajectory. Thus, each projection is acquired with a different RF phase-increment. A banding-free image can then be obtained from a single acquisition by simply applying a conventional radial reconstruction. The result is effectively an average image over the whole bSSFP frequency response profile. This approach has been shown to enable banding-free bSSFP imaging in a short scan time and even in the presence of severe field inhomogeneities. However, depending on the size of the dynamic phase-increment, the signal level of consecutive projections varies slightly. Thus, to limit the resulting artifacts, it is necessary to keep this increment small. However, a small phase-increment requires a high number of projections in order to cover the whole spectral bSSFP profile, which can significantly increase scan time. Therefore, DYPR-SSFP should be preferably applied in applications where many projections are intrinsically necessary, such as high resolution imaging. The focus of this work is another promising candidate for the combination with DYPR-SSFP that requires a high number of projections, namely 3D radial imaging.

This combination (3D DYPR-SSFP) is investigated and it is shown that it allows rapid, isotropic, banding-free bSSFP imaging with no extra expense of scan time. After a short review of the basics of conventional 2D DYPR-SSFP, the extension to 3D DYPR-SSFP is described and both approaches are compared in Bloch equation simulations. Furthermore, competing 3D radial view ordering schemes are compared and discussed. Results from 3 Tesla (T) head and knee experiments with an isotropic resolution of up to 0.56 mm are presented.

Materials and Methods

Review: 2D DYPR-SSFP

In general, the DYPR-SSFP concept can be divided into three distinct components, (i) a radial bSSFP sequence, (ii) a dynamic phase-cycle and (iii) a quasi-random view ordering. The radial acquisition scheme is required in order to guarantee the averaging of projections in the *k*-space center. The dynamic phase-cycle can be described by expanding the phase $\Phi(n)$ of the n^{th} applied RF-pulse into a Taylor series of order two: $\Phi(n) = \Phi_0 + \Delta\Phi \cdot n + \Psi \cdot n^2/2$. The corresponding derivative is $\Phi'(n) = \Delta\Phi + \Psi \cdot n$. In a conventional phase-cycled experiment [7–12], several images are acquired with different linear phase-cycles $\Delta\Phi$, yielding a constant derivative Φ' for each image. Because the positions on the frequency