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Extrinsic multiecho phase-contrast SSFP: evaluation on cardiac output measurements

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Abstract

Multiecho phase-contrast steady-state free precession (PC-SSFP) is a recently introduced sequence for flow quantification. In this multiecho approach, a phase reference and a velocity-encoded readout were acquired at different echo times after a single excitation. In this study, the sequence is validated in vitro for stationary flow. Subsequently, the sequence was evaluated on cardiac output measurements in vivo for through-plane flow in comparison to regular single gradient echo velocity quantification [phase-contrast spoiled gradient echo (PC-GE)].

In vitro results agreed with regular flow meters (RMS 0.1 cm/s). Cardiac output measurements with multiecho PC-SSFP on 10 healthy subjects gave on average the same results as the standard PC-GE. However, the limits of repeatability of PC-SSFP were significantly larger than those of PC-GE (2 l/min and 0.5 l/min, respectively, P=.001).

The multiecho approach introduced some specific problems in vivo. The difference in echo times made the velocity maps sensitive for water-fat shifts and B_0-drifts, which in turn made velocity offset correction problematic. Also, the addition of a single bipolar gradient cancelled the flow compensated nature of the SSFP sequence. In combination with the prolonged TR, this resulted in flow artifacts caused by high and pulsatile through-plane flow, affecting repeatability.

Given the significantly lower repeatability of PC-SSFP, cardiac output in turn is less reliable, thus impairing the use of multiecho PC-SSFP.

Keywords: MRI; SSFP; Multiecho; Phase-contrast; Flow quantification; Cardiac output

1. Introduction

Flow quantification is an important tool in cardiovascular magnetic resonance imaging (MRI), for example, to measure cardiac output [1–4]. The conventional approach to flow quantification utilizes spoiled gradient echo (GE) imaging technique, which inherently has a limited signal-to-noise ratio (SNR) when applied with short repetition times. With the advent of faster gradient systems flow quantification with steady-state free precession (SSFP) sequences has become feasible, three different approaches were published by Overall et al. [5], Markl et al. [6] and Pai [7]. Advantages of SSFP are shorter acquisition times and higher SNR [8,9]. The most recently published approach to flow quantification with SSFP was using multiecho phase-contrast SSFP (PC-SSFP) by Pai [7]. The multiecho PC-SSFP sequence uses a regular SSFP scheme with a second echo and a fly-back gradient between the two readout echoes. During the fly-back gradient, a bipolar gradient is applied in slice-select direction for through-plane velocity encoding (extrinsic approach). The first echo provides the phase reference while the second echo is flow-encoded.

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This approach has the advantage that it is most time-efficient in its acquisition of phase reference and flow-encoded data, compared with the single echo approaches. Also, with a multiecho approach, the steady-state does not need to be disturbed between reference and flow-encoded readouts, which can be advantageous with respect to artifact sensitivity. The extrinsic implementation of multiecho PC-SSFP permits a wide range of encoding velocities and is slightly faster than the intrinsic implementation.

A disadvantage of SSFP is its sensitivity to artifacts from pulsatile and high through-plane flow [10–13]. In the multiecho implementation, this sensitivity is slightly increased due to the longer TR and an uncompensated bipolar gradient. Another potential complication of phase-contrast measurements with a multiecho sequence is the different TEs at which the reference and flow encoded signals are read out. This makes the phase-contrast image sensitive to offsets in resonance frequency.

In this study, multiecho PC-SSFP was first evaluated in vitro using a flow phantom. To assess the clinical value of multiecho PC-SSFP, the accuracy and reliability of cardiac output measurements in healthy volunteers was investigated. The results of multiecho PC-SSFP were compared with the current clinical standard PC-GE.

2. Materials and methods

2.1. Sequence

The multiecho PC-SSFP sequence [7] was based on a regular SSFP gradient scheme extended with a second echo, where both echoes were encoded with a different velocity sensitivity (Fig. 1). Both echoes were assigned to the same cardiac phase and phase encoding step. The fly-back gradient between the two echoes was configured to have the same net area under the gradient as the first echo but with opposite sign to give the second echo the same zero'th moment. During the fly-back gradient, flow was encoded by a bipolar gradient in the slice-select direction, and the bipolar gradient was configured such that its first moment M_1 gave a phase shift of π for a v_{enc} chosen by the user:

$$M_1 = \frac{\pi}{\gamma \cdot v_{enc}} \tag{1}$$

The duration of the fly-back gradient and the bipolar flow encoding gradient was kept as short as possible — typically 1.0 ms. Velocity maps v were calculated from the phase difference between the phase image from the first readout, φ_1, and the flow-encoded image from the second readout φ_2:

$$v = \frac{\varphi_1 - \varphi_2}{\pi} v_{enc} \tag{2}$$

The multiecho PC-SSFP sequence was implemented on a 1.5-T scanner (Magnetom Sonata, Siemens, Erlangen, Germany) with a gradient performance of 40 mT/m and 200 T/m·s.

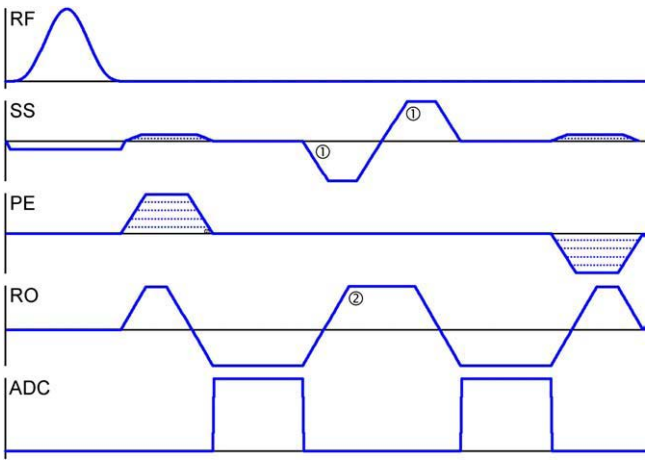

Fig. 1. Multiecho PC-SSFP sequence. The bipolar gradient ① is placed on the slice-select axis (SS) at the time interval between the two readouts for through-plane flow encoding. The readout axis (RO) contains the gradients for the two echoes and the fly-back gradient ② is placed between them.

2.2. In vitro measurements

The sequence was validated using a custom-made flow phantom. The phantom consisted of a Perspex cube with 15-cm-long edges, filled with stationary fluid. Inside the cube, fluid flowed through a tube of 4.15 mm in diameter. The flow circuit was driven by a rotary vane pump (Procon, Murfreesboro TN, USA), creating steady flow. A float displacement flow meter (Brooksmeter model 1307, Brooks Instrument, the Netherlands) was mounted in the flow circuit and was calibrated for the actual viscosity of the phantom fluid. This setup could generate flow velocities ranging up to 3 m/s, covering the physiologic range of flow velocities in the aorta of healthy humans. The phantom fluid consisted of 0.9% mass percent NaCl to load the coils, 0.05 mmol/l $MnCl_2$ to lower relaxation times (T1/T2/T2* 1505/204/198 ms, experimentally determined with MR). To give the fluid a viscosity comparable to blood (~3.5 mPa·s in normal population [14]), methylcellulose (4000 cP 0.2 vol%) was added, resulting in a viscosity of 4 mPa·s. Measurements were performed at 14 different flow settings. PC-SSFP sequence parameters were: spatial resolution 1×1×8 mm^3, matrix 256×205, FOV 262×213 mm^2, v_{enc} 150 cm/s, TR 6.4 ms, TE 1.9/4.5 ms, excitation angle 70°, bandwidth (BW) 1220 Hz/pix and 4 averages, using the body coil. PC-GE used TR 11 ms, TE 4.8 ms, excitation angle 15°, BW 190 Hz/pix; all other parameters were equal to those used with PC-SSFP.

The velocity assessed by a multiecho sequence is sensitive to B_0-offsets. This B_0-offset is influenced by the high gradient duty cycle of the PC-SSFP sequence; and thereby results in a velocity offset drift over time. To measure this drift in velocity offset as a function of time, subsequent