Magnetic Resonance Imaging 46 (2018) 106–113

Contents lists available at ScienceDirect

Magnetic Resonance Imaging

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

Original contribution

Non-contrast quantitative pulmonary perfusion using flow alternating inversion recovery at 3 T: A preliminary study

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ARTICLE INFO

Keywords:
Perfusion
Lung
FAIR
ASL
3 T

ABSTRACT

Purpose: To demonstrate the initial feasibility of non-contrast quantitative pulmonary perfusion imaging at 3 T using flow alternating inversion recovery (FAIR), and to evaluate the intra-session and inter-session reliability of FAIR measurements at 3 T.

Materials and methods: Nine healthy volunteers were imaged using our own implementation of FAIR pulse sequence at 3 T. Quantitative FAIR perfusion, both with and without larger pulmonary vessels, was correlated with global phase contrast (PC) measured blood flow in the right pulmonary artery (RPA). The same volunteers were also imaged with SPECT perfusion using technetium-99 m-macroaggregated albumin and relative dispersion (RD) was assessed between FAIR and SPECT perfusion. Four additional healthy volunteers were evaluated for FAIR repeatability, using intra-class correlation coefficient (ICC) and Bland-Altman analysis. $p < 0.05$ was considered statistically significant.

Results: FAIR perfusion across all subjects was 858 ± 605 mL/100 g/min (with vessels) and 629 ± 294 mL/100 g/min (without vessels) and correlated significantly with the PC measured blood flow in the RPA ($r = 0.62$, $p < 0.01$ with vessels; $r = 0.73$, $p < 0.001$ without vessels). The median RD of FAIR perfusion across all subjects was 0.73 (with vessels) and 0.49 (without vessels), compared against 0.23 with SPECT perfusion. The intra/inter-session ICC of FAIR perfusion with vessels was 0.95/0.59 and improved to 0.96/0.72, when vessels were removed.

Conclusions: Non-contrast quantitative pulmonary perfusion imaging using FAIR is feasible at 3 T. This may serve as a reliable method to assess regional lung perfusion at 3 T to characterize and monitor treatment response in chronic lung disease without the concerns of repeated exposure to ionizing radiation or the accumulation of exogenous contrast agent.

1. Introduction

Chronic lung diseases are among the most common causes of disability worldwide [1]. These diseases heterogeneously disrupt pulmonary perfusion, increase pulmonary vascular resistance and can lead to reduced oxygenation of the blood, pulmonary hypertension, and eventually right heart failure. Regional mapping of perfusion can be performed clinically with nuclear imaging techniques either using planar scintigraphy or single photon emission computed tomography (SPECT) using radioactive technetium (^{99m}Tc) [2]. However, major limitations of these nuclear imaging techniques include inadequate spatial resolution for detecting small variations in perfusion, as well as exposure to ionizing radiation. Iodine-enhanced CT can provide higher spatial resolution blood volume images (commonly referred to as perfusion images), however, CT also includes exposure to ionizing radiation and the risk associated with intravenous iodinated contrast material injection. Furthermore, repeated exposure to ionizing radiation, particularly in children and younger patients who may need repeated scans for monitoring disease evolution and/or therapy response, remains a concern for these techniques [3].

Magnetic resonance imaging (MRI) based on dynamic contrast material-enhancement can provide high spatial resolution perfusion maps, and has been well-correlated with perfusion scintigraphy [4,5]. The need for administration of exogenous contrast, however, restricts

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https://doi.org/10.1016/j.mri.2017.11.007
Received 20 August 2017; Received in revised form 6 November 2017; Accepted 13 November 2017

the number of repeated measurements in a subject and is highly dependent on the timing of the acquisition [6]. Additionally, gadolinium based contrast agents have been implicated in potential risks such as nephrogenic systemic fibrosis [7] and cumulative accumulation in the brain [8]. Alternative gas exchange methods using regional gas diffusion measurements based on hyperpolarized xenon-129 is promising [9], but the extension to routine clinical applications is impeded by high costs associated with the polarizer, additional scanner hardware and personnel expertise combined with limited availability [10]. Newer techniques such as Fourier Decomposition (FD) has also been recently introduced as another perfusion imaging technique [11,12].

Alternatively, arterial spin labeled (ASL) MRI can provide quantitative perfusion maps noninvasively, using blood as an endogenous tracer. One such method, Flow Alternating Inversion Recovery (FAIR), has been extensively studied for pulmonary perfusion imaging at 1.5 T [13–17]. This inversion recovery-based technique creates perfusion-weighted images by applying a selective inversion covering only the imaging region for a control image, and non-selective inversion to invert all inflowing blood for a label image. The difference between these two images will be proportional to the perfusion in the imaging plane. Despite being extensively studied at 1.5 T, applications in the lungs at 3 T have been lacking. Extending the FAIR technique to 3 T should provide increased signal to noise ratio (SNR) due to the higher field strength and prolonged T1 of blood [18], which could require fewer signal averages and reduce scan times. This increase in SNR has been confirmed to be significant in brain perfusion imaging at 3 T [19], however, pulmonary perfusion imaging using FAIR at 3 T has not been demonstrated before, possibly due to concerns associated with increased magnetic susceptibility effects.

Thus, the purpose of this study was to demonstrate the initial feasibility of non-contrast quantitative pulmonary perfusion imaging at 3 T using FAIR, and to evaluate the intra-session and inter-session reliability of FAIR measurements at 3 T.

2. Materials and methods

2.1. Subjects

This was a prospective, HIPAA-compliant study, approved by the institutional review board. All subjects provided written informed consent prior to their participation in the study. Nine healthy volunteers (age 42 ± 17 years; 6 men 41 ± 17 years and 3 women 42 ± 20 years) participated in the study. As part of a broader pulmonary perfusion study, these subjects were also imaged using SPECT perfusion. Additionally, four healthy volunteers (age 42 ± 14 years; one 59-year-old man and 3 women 36 ± 9 years) were recruited to evaluate the intra-session and inter-session reliability of FAIR measured pulmonary perfusion at 3 T.

2.2. MR imaging

All of the MR imaging was performed on a 3 T scanner (Ingenia, Philips Healthcare, Best, The Netherlands) using our own implementation of the FAIR sequence including an extra radiofrequency pulse (similar to FAIRER) for initial saturation [14]. Subjects were positioned in the magnet head-first, supine, with the anterior torso coil, along with respiratory bellows and leads for ECG gating. The body coil was used for signal transmission, while the anterior torso coil and the posterior coils embedded in the table were used for signal reception. ECG gating was used for cardiac triggering, while the respiratory bellows were used for monitoring and coaching the subject's breathing. The FAIR sequence began by saturating the imaging region, followed by labeling with a pair of slice-selective and slab-selective inversions in successive repetitions, using a hyperbolic secant pulse centered on the imaging region (Fig. 1). The slice-selective inversion thickness was set to three times the imaging plane thickness to ensure complete inversion of the spins in the imaging plane (control image) and the slab-selective inversion was set to ten times the slice-selective inversion (label image). A post-labeling delay of one cardiac period (e.g. 1 s for a heart rate of 60 beats per min) was used to allow labeled blood to perfuse the lungs [13]. A single-shot turbo spin echo (SShTSE) readout with partial Fourier along the phase encoding direction was used to minimize the sensitivity to B_0 inhomogeneities that are encountered at air/tissue interfaces in the lungs. The FAIR sequence was cardiac-triggered using ECG to ensure diastolic acquisition in the following cardiac cycle to minimize signal variations due to pulsatile flow [13].

Three pairs of control/label images of a single slice were acquired within an 18 s end-expiration breathhold acquisition using the following parameters: TR = 3 s; TE = 46 ms; 3 × 3 mm^2 in-plane resolution; 15 mm slice thickness; 544 Hz/pixel bandwidth; 0.55 partial k-space factor. 2D sagittal and coronal perfusion images of a single slice were acquired in separate breathhold acquisitions for each volunteer.

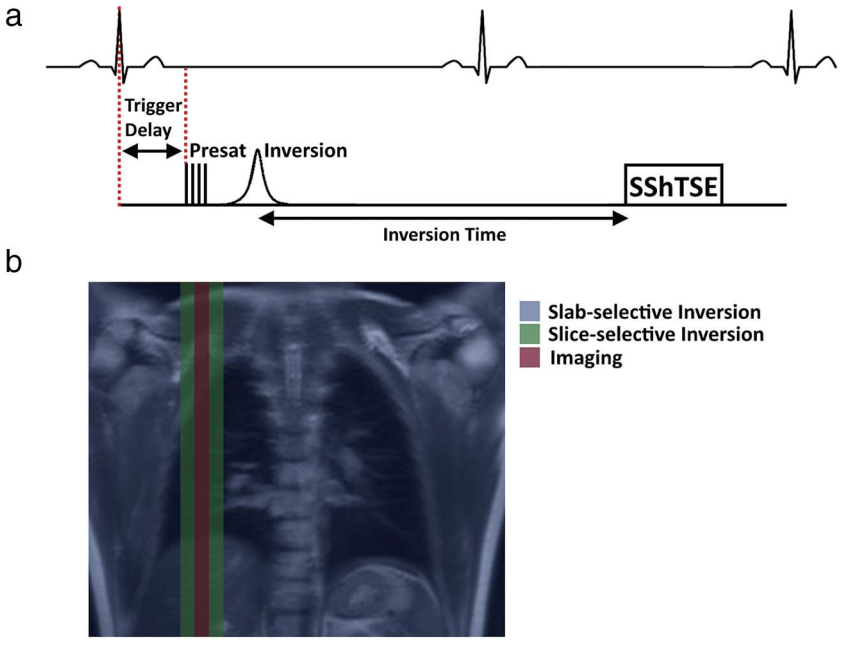

Fig. 1. A schematic of the ECG-triggered FAIR sequence. (a) On cardiac trigger, the pre-saturation followed by slice/slab selective inversion pulses are applied. After an inversion delay (e.g. 1 R-R interval), data are acquired using a SShTSE acquisition during the diastolic phase of the subsequent cardiac cycle. (b) Schematic of the coronal image showing the sagittal imaging slice (red), slice-selective inversion (green) and slab-selective inversion (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)