Original Investigation

Volumetric Arterial Spin-labeled Perfusion Imaging of the Kidneys with a Three-dimensional Fast Spin Echo Acquisition

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Abbreviations and Acronyms

2D two-dimensional
3D three-dimensional
ASL arterial spin labeling
BGS background suppression
FOCI frequency-offset-corrected inversion
FSE fast spin echo
GRASE gradient and spin echo
MRI magnetic resonance imaging
pCASL pseudo continuous arterial spin labeling
RCC renal cell carcinoma
ROI region of interest
SNR signal-to-noise ratio
SSFSE single-shot fast spin echo
T1 T_1 relaxation constant
T2 T_2 relaxation constant

Rationale and Objectives: Renal perfusion measurements using noninvasive arterial spin-labeled (ASL) magnetic resonance imaging techniques are gaining interest. Currently, focus has been on perfusion in the context of renal transplant. Our objectives were to explore the use of ASL in patients with renal cancer, and to evaluate three-dimensional (3D) fast spin echo (FSE) acquisition, a robust volumetric imaging method for abdominal applications. We evaluate 3D ASL perfusion magnetic resonance imaging in the kidneys compared to two-dimensional (2D) ASL in patients and healthy subjects.

Materials and Methods: Isotropic resolution ($2.6 \times 2.6 \times 2.8$ mm^3) 3D ASL using segmented FSE was compared to 2D single-shot FSE. ASL used pseudo-continuous labeling, suppression of background signal, and synchronized breathing. Quantitative perfusion values and signal-to-noise ratio (SNR) were compared between 3D and 2D ASL in four healthy volunteers and semiquantitative assessments were made by four radiologists in four patients with known renal masses (primary renal cell carcinoma).

Results: Renal cortex perfusion in healthy subjects was 284 ± 21 mL/100 g/min, with test-retest repeatability of 8.8%. No significant differences were found between the quantitative perfusion value and SNR in volunteers between 3D ASL and 2D ASL, or in 3D ASL with synchronized or free breathing. In patients, semiquantitative assessment by radiologists showed no significant difference in image quality between 2D ASL and 3D ASL. In one case, 2D ASL missed a high perfusion focus in a mass that was seen by 3D ASL.

Conclusions: 3D ASL renal perfusion imaging provides isotropic-resolution images, with comparable quantitative perfusion values and image SNR in similar imaging time to single-slice 2D ASL.

Key Words: MRI; arterial spin labeling; perfusion; blood flow; renal cell carcinoma; kidney disease.

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INTRODUCTION

Imaging the distribution and heterogeneity of tissue perfusion is an important component of clinical identification and characterization of primary and metastatic cancer. Quantitative perfusion measurements in tumors may be important for monitoring disease progression (1), in particular in response to antiangiogenic therapy (2–6), and may play a role in assessing the early changes of disease or in understanding normal physiology. There is increasing interest in perfusion measurements as a biomarker for assessing renal function and for characterizing renal masses. Quantitative perfusion is reduced in renal insufficiency and in hemodynamically significant renal artery stenosis (7–10). In renal cell carcinoma (RCC), perfusion has proven value because of the relationship between angiogenesis, prognosis, and response to different targeted therapies in these tumors (11–17).

Arterial spin labeling (ASL) is a well-established method for measuring tissue perfusion (18–20) that has been widely used in quantitative perfusion measurements of the brain with application to brain tumors (21–24), cerebrovascular disease and stroke, epilepsy, and dementia (25). A major advantage of ASL is the relative ease with which ASL images can be converted to quantitative images of tissue perfusion. ASL employs external magnetic fields to label nuclear magnetization of endogenous water in arterial blood and then observes the effect on tissue signal after the water flows into and diffuses throughout the tissue. Freely diffusible endogenous water is an excellent tracer for perfusion that compares well to intravenously administered contrast material, because of its lower risk for renal patients and because signal is linear in concentration and independent of venous bolus dynamics and vessel permeability effects that complicate quantification of perfusion with intravenous contrast agents.

ASL has been successfully applied to imaging perfusion in organs and lesions in the abdomen (8,10–13,15,16,26–40). Initial studies have focused on single-slice two-dimensional (2D) imaging. Although these approaches have met with some success, their spatial coverage limits the ability to visualize the full extent of disease. Multislice 2D imaging with ASL is possible (33), but sequential imaging after ASL preparation causes time delays that complicate quantification across slices and interfere with strategies for reducing motion errors by background suppression (BGS). BGS (41) has previously been shown to reduce signal fluctuations from physiological motion (32), particularly for ASL in the abdomen (32,41,42). Because full BGS can be achieved for only a short time, it favors combination with three-dimensional (3D) acquisitions where the entire volume can be excited at a single time point. Although segmented 3D volumetric acquisition requires more time to acquire the entire image than 2D imaging, multiple averages of 2D acquisitions are usually required to achieve sufficient signal-to-noise ratio (SNR) so scan times are often comparable. In addition, acquiring 3D images with isotropic resolution allows for reformatting of the image data to enhance lesion characterization as has been widely implemented for contrast-enhanced magnetic resonance imaging (MRI) of abdominal pathology, including renal masses (43,44).

A 3D volumetric approach for renal ASL has recently been reported (34,40) and applied to the assessment of renal perfusion in healthy kidney donors (39), but these studies were limited to assessing whole-kidney perfusion in healthy volunteers. In this work, we implement and evaluate a 3D volumetric, isotropic resolution ASL technique using a fast spin echo (FSE) acquisition. After evaluation in healthy volunteers, we assess semiquantitatively its use in patients with primary RCC. Here, the benefit of 3D reformatting is expected to be significant for evaluating renal masses. To the best of our knowledge, this is the first such demonstration of an isotropic, 3D ASL measurement in renal cancer patients.

MATERIALS AND METHODS

Four healthy volunteers (two female, aged 23–53, average 31) and four patients referred for presurgical MRI evaluation of known renal masses (2 female, aged 39–67, average 53) were imaged in this study. Healthy volunteers had no contraindications to MRI and had no known recent health problems. Four patients with renal masses on one kidney undergoing MRI examination prior to nephrectomy consented to additional imaging sequences. In one volunteer, only one kidney was evaluated owing to prior surgery on the other kidney. No subjects were excluded.

MRI Imaging

This study was performed on a 1.5 T EXCITE HDx MRI scanner using the body coil for transmission and the product eight-channel body array receiver (GE Healthcare, Waukesha, WI).

ASL

The pseudo continuous arterial spin labeling (pCASL) technique was used in all cases and has been previously described in detail (45). Labeling is applied for 1.5 seconds (average radiofrequency strength 1.4 μT, average/maximum labeling gradient strength 0.7/7 mT/m) followed by a 1.5-second postlabeling delay (46) before image acquisition. The labeling plane was positioned slightly inferior to the diaphragm, not intersecting the heart, to label blood in the descending aorta, as shown in Figure 1.

BGS

Spatially selective presaturation pulses were played 4100 ms prior to imaging followed by a spatially selective "C-shaped" frequency-offset-corrected inversion pulse (47) (10.8-kHz bandwidth, 15.36 ms, $\beta = 809\ s^{-1}$, $\mu = 3.9$), chosen for superior spatial selectivity, played 3000 ms prior to imaging. Four additional nonselective Silver-Hoult pulses (10-ms duration, 1.8-kHz bandwidth, $\beta = 1242\ s^{-1}$, $\mu = 4.5$) were played at times 1500, 680, 248, and 57 ms prior to imaging, as shown