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A 3D balanced-SSFP Dixon technique with group-encoded k-space segmentation for breath-held non-contrast-enhanced MR angiography

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Abstract

A three-dimensional balanced steady state free precession (b-SSFP)-Dixon technique with a novel group-encoded k-space segmentation scheme called GUINNESS (**G**roup-encoded **U**ngated **I**nversion **N**ulling for **N**on-contrast **E**nhancement in the **S**teady **S**tate) was developed. GUINNESS was evaluated for breath-held non-contrast-enhanced MR angiography of the renal arteries on 18 subjects (6 healthy volunteers, 12 patients) at 3.0 T. The method provided high signal-to-noise and contrast renal angiograms with homogeneous fat and background suppression in short breath-holds on the order of 20 seconds with high spatial resolution and coverage. GUINNESS has potential as a short breath-hold alternative to conventional respiratory-gated methods, which are often suboptimal in pediatric subjects and patients with significant diaphragmatic drift/sleep apnea.

Keywords

non-contrast-enhanced MR angiography; balanced steady state free precession; Dixon fat-water separation

Introduction

Contrast-enhanced MR angiography (CEMRA) is commonly used in the diagnosis and evaluation of renal artery stenosis (RAS) [1–2]. The recent association of nephrogenic systemic fibrosis (NSF) with administration of Gadolinium-based contrast agents [3] in some patients has spurred a renewed interest in non-contrast-enhanced MRA methods. This is particularly of concern in patients with suspected renal artery disease, who often have compromised renal function and low glomerular filtration rates.

Traditionally, two- and three-dimensional time-of-flight (TOF) techniques [4–5] or phase-contrast-based methods [6] have been used for non-contrast-enhanced angiography. In TOF,

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a thin-slab, RF-spoiled gradient echo sequence oriented orthogonal to the flow and with additional superior or inferior saturation bands yields images with suppressed arterial or venous signal by exploiting the in-flow effect. However, TOF-based imaging suffers from saturation effects arising from blood remaining in the slab over several TRs, typically in vessels not orthogonal to the imaging slab or in vessels with slow blood flow. Phase-contrast-based methods perform better but their scan times tend to be very long, resulting in compromised image quality. Furthermore, venous suppression is poor, requiring more sophisticated post-processing techniques for artery-vein segmentation.

Balanced steady state free precession (b-SSFP) imaging [7–13] has shown great promise due to its high signal-to-noise ratio (SNR), SNR efficiency, favorable flow properties, and short scan times. Recently, arterial spin labeling (ASL) based schemes with b-SSFP imaging segments have been used successfully in imaging the renal arteries, first reported by Katoh et al [7] and more recently by other groups [8–13]. These schemes involve application of a slab-selective inversion tagging pulse to suppress the background and venous signal (i.e., IR preparation), while using a b-SSFP readout segment to image the arterial inflow that has occurred during the inversion period. The acquisition is usually electrocardiography (ECG) gated to acquire the data in mid-diastole to minimize motion blurring and flow artifacts. All of these methods employ some form of respiratory gating using either navigator echoes or respiratory bellows to acquire only a small number of k-space views in each respiratory cycle. The typical acquisition time of a respiratory-gated, 3D b-SSFP sequence is 2–4 minutes, depending on the subject’s respiratory rate and rhythm. Navigator gating has been shown to fail in situations where there is a diaphragmatic drift or irregular respiratory rhythm [14]. At our institution, we found respiratory gating to be suboptimal in roughly 20% of the cases, resulting in poor image quality. Breath-held versions of the 3D b-SSFP sequence have also been reported [8,11]. However, these achieve short breath-holding times by increasing the slice thickness and/or reducing the slab coverage, resulting in compromised image quality and reduced sensitivity [9].

Robust fat suppression is a challenge especially at high field strengths due to B_0 and B_1 inhomogeneities. The most popular method for fat suppression involves application of a lipid-selective inversion pulse prior to acquisition of a set of k-space views. However in the case of b-SSFP imaging, interleaving the fat suppression segment perturbs the steady state, causing ghosting artifacts. While these artifacts can be mitigated to some extent using catalyzing schemes such as the ½α-½TR scheme [15], explicit fat suppression techniques, due to their spectral selectivity, are sensitive to B_0 and B_1 inhomogeneities. This often causes saturation of the water signal, leading to SNR loss. Another significant limitation of using conventional fat suppression techniques is the restriction of k-space view ordering to centric or centric-like schemes in order to maximize fat suppression while reducing scan times. The number of k-space views acquired per fat-suppression pulse is limited due to the short T_1 of the lipid species, further restricting scan time reduction. Two- and three-point Dixon fat-water separation schemes [16–17] with robust phase unwrapping methods have been demonstrated to be useful in a variety of clinical scenarios. They are far less sensitive to B_0 and B_1 inhomogeneities and, most importantly, permit the use of arbitrary k-space segmentation schemes, which can traverse k-space more efficiently.

A short breath-held 3D sequence with robust fat suppression and high spatial resolution and coverage would be very advantageous in a clinical setting for increasing patient throughput and comfort. We propose GUINNESS (**G**roup-encoded **U**ngated **I**nversion **N**ulling for **N**on-contrast **E**nhancement in the **S**teady **S**tate) – a balanced SSFP-Dixon 3D acquisition with a group-encoded k-space segmentation scheme for non-contrast-enhanced renal MRA in a single short breath-hold, without compromising spatial resolution or coverage.

Methods

Pulse sequence

A dual-echo, bipolar-readout, 3D b-SSFP sequence was developed as shown in Figure 1a. Optimal fat-water out-of-phase and in-phase TEs of 1.2–1.4 ms and 2.4–2.6 ms were routinely achieved by using a high receiver bandwidth (±142–167 kHz) and fractional-echo readouts (echo fraction 0.85). The use of short TRs (4.5 ms or less) minimized b-SSFP banding artifacts as well as the overall scan time, whilst enabling high spatial resolution (256–320 points) along the readout direction. A two-point Dixon reconstruction algorithm with robust phase estimation of Ma et al. [16] was used for fat-water separation. An axial slab-selective hyperbolic secant inversion pulse extended spatially in the inferior direction relative to the acquisition slab was used to simultaneously effect venous and background suppression. The inversion time, optimized for both background/venous blood suppression and inflowing arterial blood signal at 3T, was 1300ms.

In order to reduce the scan time to a short breath-hold of the order of 22 seconds or less without compromising spatial resolution and coverage, we developed a novel group-encoded view-ordering scheme. The GUINNESS group-encoded k-space segmentation scheme with each “group” or segment depicted in a different color is shown in Figure 1b. Within each group, k-space views are reordered in a centric k_z and sequential k_y fashion. Furthermore, the following points were considered while creating this view-ordering scheme:

- **a.** views within a segment are grouped together contiguously to minimize large jumps in gradients, minimizing eddy current-induced artifacts;
- **b.** sequential and centric view-ordering properties were retained for contrast manipulation and immunity to breath-hold loss;
- **c.** non-separable sampling patterns, such as 2D self-calibrated parallel imaging [18], as well as skipping the corners of k-space (i.e. acquisition of an elliptical region of k_y-k_z space) were used to further reduce scan time.

MR Acquisitions

Eighteen subjects (12 patients, 6 healthy volunteers) were imaged on a 3T MR750 system (GE Healthcare, Waukesha, WI) using an 8-channel torso array coil under an IRB-approved protocol. Indications for clinical renal MRA included chronic renal insufficiency or suspected renovascular hypertension in the setting of poorly controlled blood pressure. Examinations in patients also included conventional contrast-enhanced 3D MRA, which were performed after the GUINNESS non-contrast scans. Healthy volunteers were also scanned but no contrast was administered. In some volunteers, a respiratory-triggered 3D b-SSFP acquisition (Inhance, GE Healthcare, Waukesha) with matching parameters to GUINNESS was also performed. The following imaging parameters were used for all GUINNESS acquisitions: 55° flip, ±142–167 kHz receiver bandwidth, TR/TE1/TE2 4.8/1.2–1.4/2.4–2.6 ms, (256–320)×(192–224) matrix, 35–37 cm FOV, 1.4–2 mm section thickness, 32–40 slices, 800 views-per-segment, 1300 ms inversion time. A self-calibrating, hybrid-space parallel imaging scheme with a net acceleration factor of 2 was used in the *y* phase encoding direction [18]. The overall breath-holding time was 20–24s.

Optimization of views-per-segment (VPS)

In order to minimize breath-holding times and optimize the arterial blood-background contrast, we varied the number of views acquired per inversion recovery (IR) segment (VPS). Following MATLAB Bloch simulations of IR-prepared b-SSFP with a 55° flip angle to characterize the venous/background signal as a function of VPS, *in vivo* GUINNESS acquisitions (scan parameters same as above) at four different VPS of 300, 800, 1000 and 1200 were acquired from a healthy subject. The breath-holding times were 25s, 22s, 20s and 18s respectively.

Results

All eighteen examinations of clinical patients and healthy volunteers yielded diagnostic quality images as assessed by the radiologist (JFG). In the clinical group, three patients had a significant renal artery stenosis (defined as luminal narrowing greater than 50%), including one patient with fibromuscular dysplasia. In these cases, as well as the negative studies, the results of the GUINNESS acquisition were in agreement with conventional 3D CE MRA. No significant renal artery stenosis was observed in images of healthy volunteers acquired with either respiratory-triggered 3D b-SSFP or GUINNESS.

Abdominal sections of a volunteer from a conventional fat-suppressed b-SSFP sequence (a) and a b-SSFP with a 2-point Dixon based fat-water separation (b) are compared in Fig. 2. Note the uniformity and the degree of fat suppression achieved in (b) using the Dixon based fat-water separation compared to conventional fat suppression (a). The quality of fat suppression, image SNR and CNR are qualitatively better in the GUINNESS acquisitions (b).

Figure 3 shows Bloch-equation simulations of venous/background signal using an IR-prepared b-SSFP sequence with a flip angle of 55° and TR/TI of 4.5/1300 ms. Note that beyond VPS=300, the venous/background signal M_{xy} (solid line) does not vary and reaches a steady-state value. Maximum intensity projections (MIPs) from four GUINNESS acquisitions with views-per-segment (VPS) values of 300, 800, 1000 and 1200 respectively, acquired from a healthy subject are shown in Figure 4. The breath-holding times were 25s, 22s, 20s and 18s respectively. Note the high arterial-background contrast and inflow enhancement achieved in a short breath-hold time in (b) (VPS=800) compared to (a), (c), and (d). Increasing the VPS beyond 800 reduces the breath-holding time further but leads to increased venous signal, presumably due to slower venous inflow (solid arrows) and increased hepatic vascular signal (dashed arrow). After taking inflowing venous blood into account, a VPS of 800 was determined to be an optimal tradeoff between short breath-hold times, good background/venous suppression and high arterial in-flow signal.

Volume renderings of 22s breath-hold GUINNESS acquisitions from two healthy subjects are shown in Fig. 5. Note the degree of blood-background contrast, fat and venous suppression, and the ability to visualize distal segments as well as the intra-renal artery segments using the proposed sequence. Figure 6 compares a conventional contrast-enhanced MRA scan acquired using a 3D SPGR sequence (a) and a 22s breath-hold GUINNESS acquisition (b) on a patient with fibromuscular dysplasia (FMD). Note the beaded appearance of the right renal arteries discernible in both the images, with subtle involvement of the left renal artery. Figure 7 compares MIP images from a conventional contrast-enhanced MRA acquisition (a) and a 23s breath-hold GUINNESS acquisition (b) from a 51 year old patient with hypertension and mild renal insufficiency, clearly depicting the stenosis in the right renal artery as well as the small superior accessory right and left renal arteries.

Discussion

We have demonstrated a promising, new balanced-SSFP-Dixon sequence for imaging the renal arteries in a single, short breath-hold. The GUINNESS technique is able to offer good fat suppression with good image quality, resulting in excellent visualization of the renal vasculature. This is especially significant at 3T where conventional fat suppression techniques are often suboptimal due to increased B_0 and B_1 inhomogeneities. More importantly, the use of a Dixon-based fat-water separation technique enabled us to use a non-standard view-ordering scheme with significantly higher VPS (~800). The long segmentation length was crucial for reducing the breath-hold time without compromising coverage or spatial resolution, a drawback noted in previously reported breath-hold based schemes [8,11]. In conventional fat suppression techniques, a centric k-space ordering scheme is essential for optimal fat suppression. However, the number of k-space views that is acquired for each fat suppression segment is limited due to the short T_1 of lipids, prolonging scan times. The Dixon-based fat water separation scheme eliminated any modulation of fat magnetization and enabled the use of more efficient non-centric k-space ordering schemes such as our group-encoded scheme. The background and venous suppression were high even at large VPS values due to the longer T_1 of venous blood and background tissue and the use of large b-SSFP flip angles (Fig. 3 –4).

A bipolar readout was employed to shorten the TR, which minimized b-SSFP banding artifacts and overall scan times. However, a bipolar readout could exacerbate the fat-water chemical shift artifact due to polarity reversal, which reverses the direction of the chemical shift from one echo to the next. The use of a high sampling bandwidth and fractional echo readouts minimized this chemical shift artifact. Another potential artifact source is echo misalignment due to differential gradient group delays (similar to that in echo-planar imaging), which also reverses direction from the first to the second echo. A first-order phase-correction term in the Dixon reconstruction algorithm ensured alignment of both echoes, effectively eliminating any residual ghosting.

One drawback of most inflow-based techniques is the relative insensitivity to slow flow or saturation resulting from thicker slab acquisitions. This is a principal cause of flow voids and poor SNR in classic TOF-based methods especially in the renal arteries which are oriented orthogonal to the slice direction (in an axial slab) and hence subject to in-plane saturation effects. However, in ASL-prepared b-SSFP sequences such as ours, the inflow duration is over the inversion time (order of one second) compared to classical TOF methods where it is of the order of a TR (10–20 ms) resulting in significantly increased inflow even in slow flow cases. A more extensive study on patients with renal artery stenosis quantifying the sensitivity and specificity of our technique compared to conventional contrast-enhanced MRA is currently underway.

We eliminated the need for respiratory and ECG gating, potentially enabling GUINNESS for application in a variety of clinical scenarios, e.g., pediatric subjects or adults who have a difficulty in maintaining a steady respiratory rhythm. Although navigator echo based gating can be used to eliminate breath-holding, Taylor et al [14] have demonstrated diaphragmatic drift and irregular breathing patterns due to sleep apnea, for example. This can result in significant artifacts, especially with prolonged scan times. While we have not perceived a need for ECG gating, it is conceivable that the long acquisition interval (~800 TRs) can cause flow artifacts when there is considerable variation in blood flow over the acquisition window in patients with very high heart rates or with complex aortic flow patterns. In such cases, ECG gating might be useful in mitigating flow artifacts. Our k-space acquisition scheme could be easily modified to acquire a small fraction of the central k_y-k_z space during mid-diastole and acquiring the remainder of k-space in the same segmented fashion, maintaining the short breath-hold times. By adding respiratory gating to just that central segment and acquiring the peripheral k-space in a free-breathing fashion, the scan efficiency of our sequence could be combined with the motion robustness of a traditional respiratory gated acquisition.

While we have confined to the renal arteries in this imaging study, the GUINNESS pulse sequence can also be used to image the hepatic and carotid arteries, where conventional fat suppression is often challenging, due to increased field inhomogeneities. Imaging anatomical regions more complex than the renal vasculature (which is ideal for acquisition using an axial slab) will require pulse sequence modifications to perform multiple or an oblique spatial inversion band for eliminating venous contamination. Preliminary results using GUINNESS for imaging the hepatic arteries and the renal arteries in a coronal plane have been promising.

In conclusion, GUINNESS is a robust breath-held non-contrast-enhanced method for imaging the renal arteries with no compromise in spatial resolution or coverage. The use of a Dixon-based fat suppression technique provided robust fat suppression as well as removed any restrictions on k-space traversal, enabling us to use the efficient group-encoded scheme for reducing scan times. GUINNESS could be a valuable adjunct to navigator-gated methods especially in patients with irregular breathing or sleep apnea.

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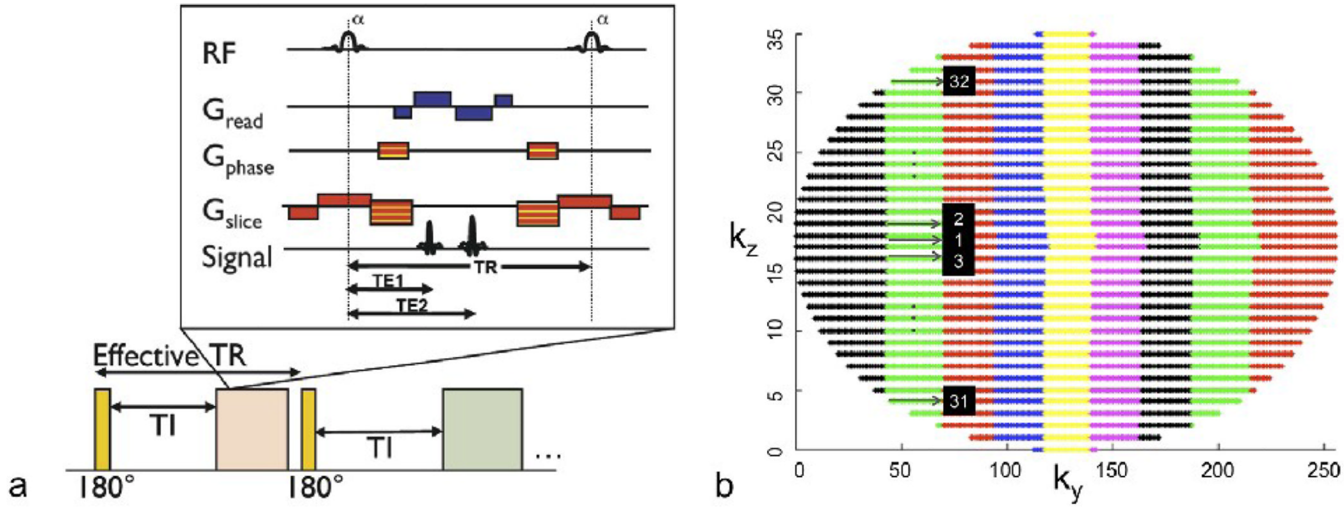

Figure 1.

Inversion-recovery prepared bipolar dual-echo balanced steady state free precession sequence (a) and the group-encoded k-space segmentation scheme used in GUINNESS (b). Within each segment (different color), k-space views are reordered in a centric k_z and sequential k_y fashion to minimize eddy currents and maximize image contrast.

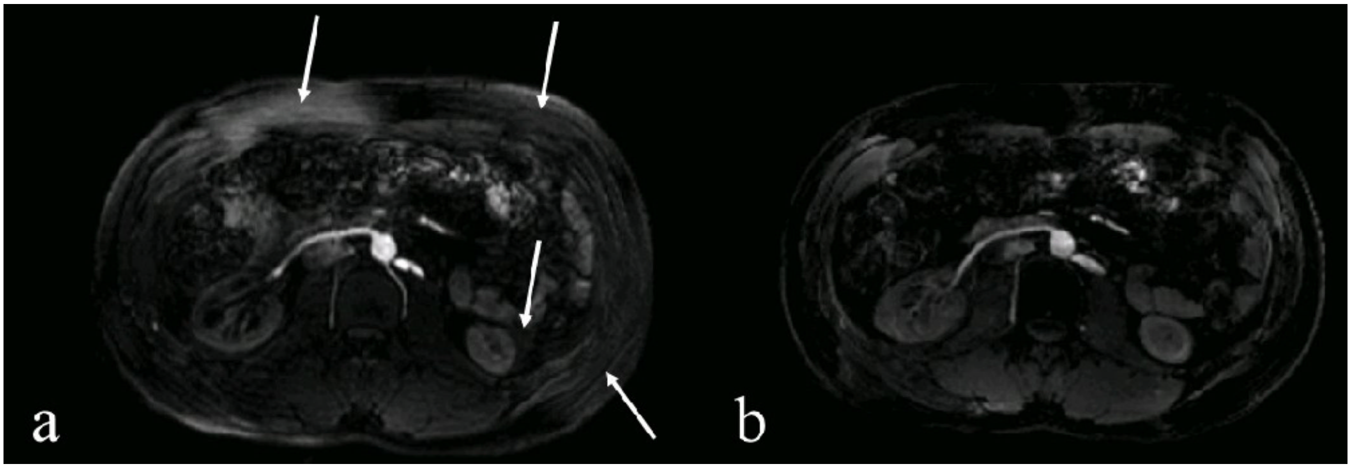

Figure 2.
Comparison of axial sections from a conventional fat-saturated b-SSFP sequence (a) and a b-SSFP with a 2-point Dixon based fat-water separation (b), demonstrating the superiority of Dixon-based fat-water separation. The arrows highlight areas of sub-optimal fat suppression with conventional lipid-selective IR-prep.

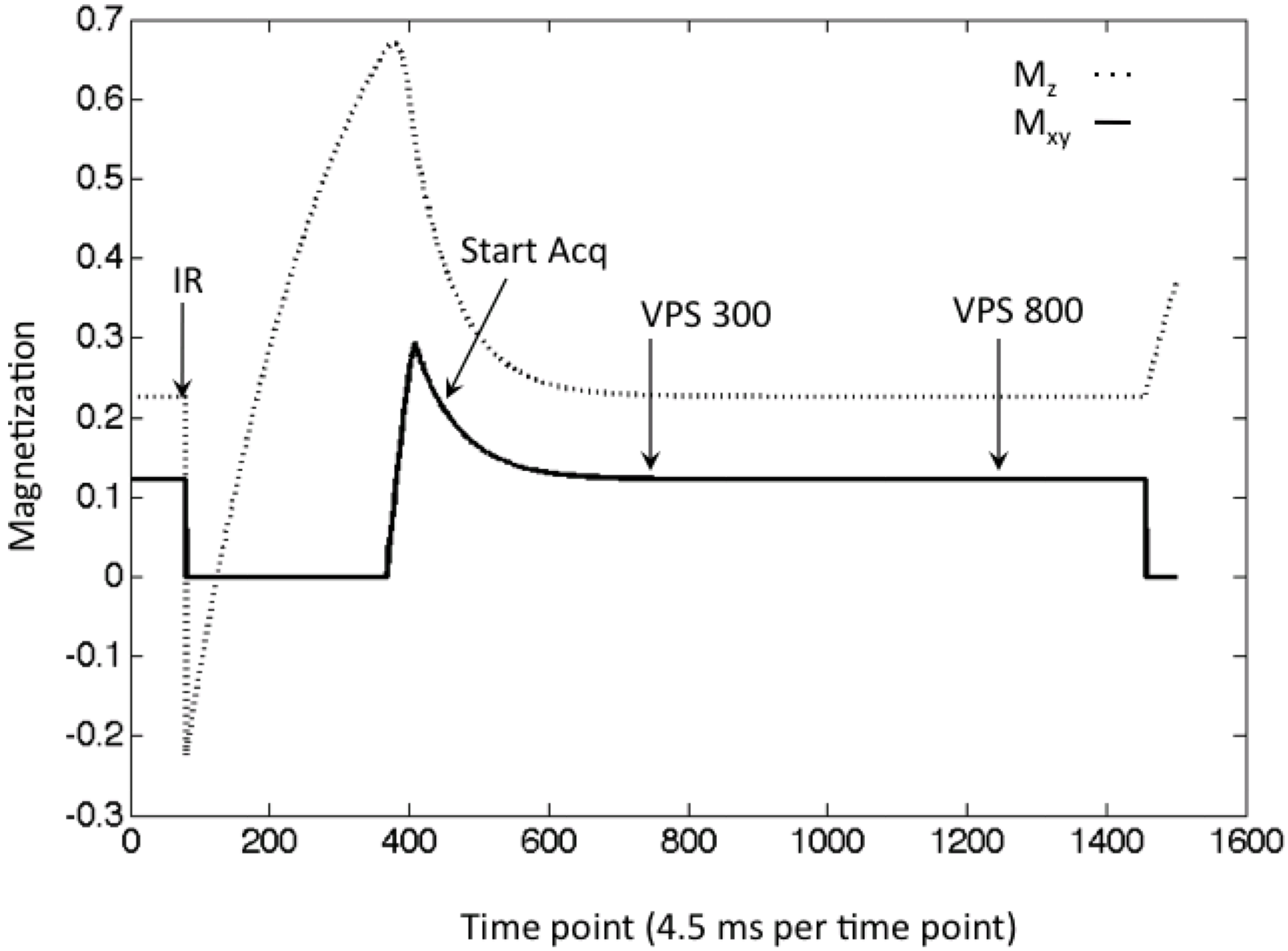

Figure 3.
Bloch-equation simulations of venous/background signal using an IR-prepared b-SSFP sequence (M_z - dashed line, M_{xy} - solid line). Note that beyond VPS=300, the venous/background signal M_{xy} reaches a steady-state value.

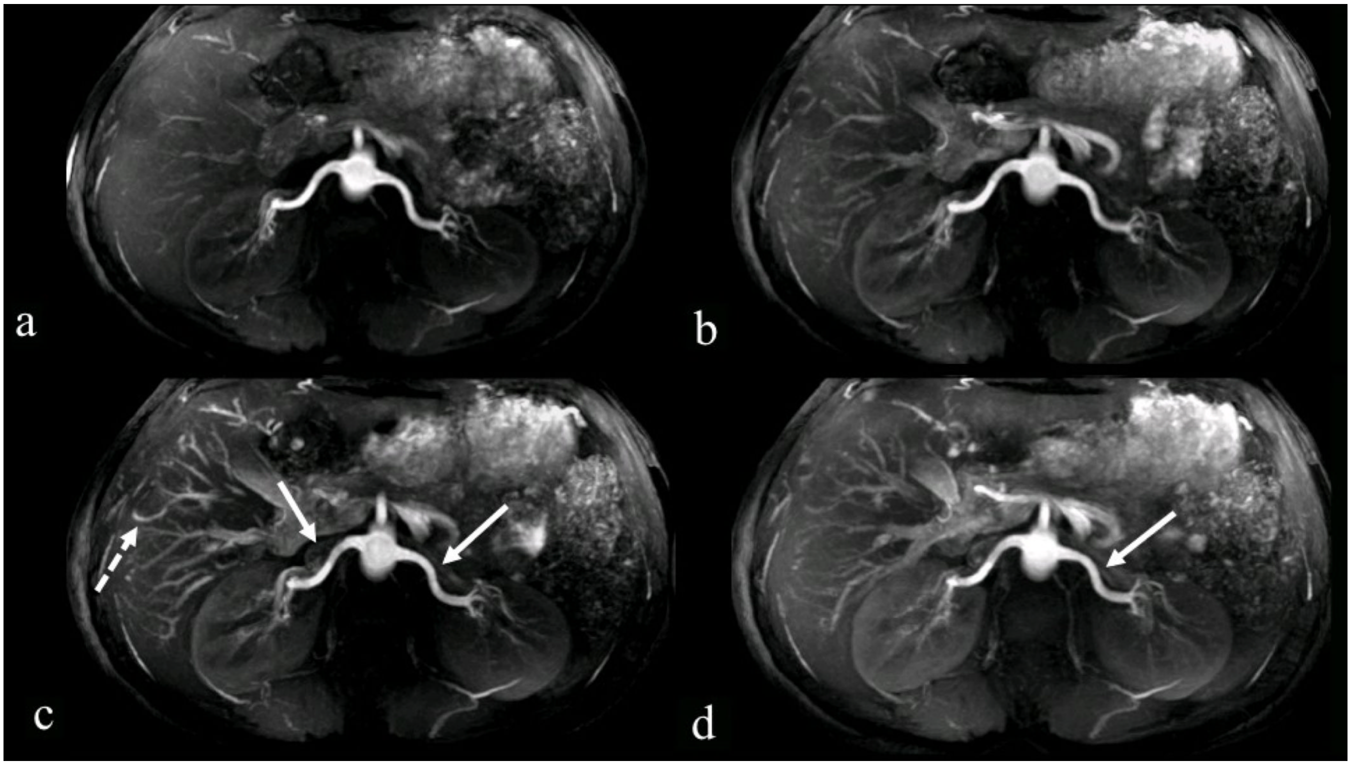

Figure 4.
Comparison of maximum intensity projections from GUINNESS acquisitions with views-per-segment (VPS) values of 300 (a), 800 (b), 1000 (c), and 1200 (d) acquired from a healthy subject. Note the increasing venous signal with increasing VPS (renal vein, inferior vena cava: solid arrows) and the increased hepatic vascular signal with increasing VPS (dashed arrow). A VPS value of 800 is an optimal trade-off between high contrast and short scan time.

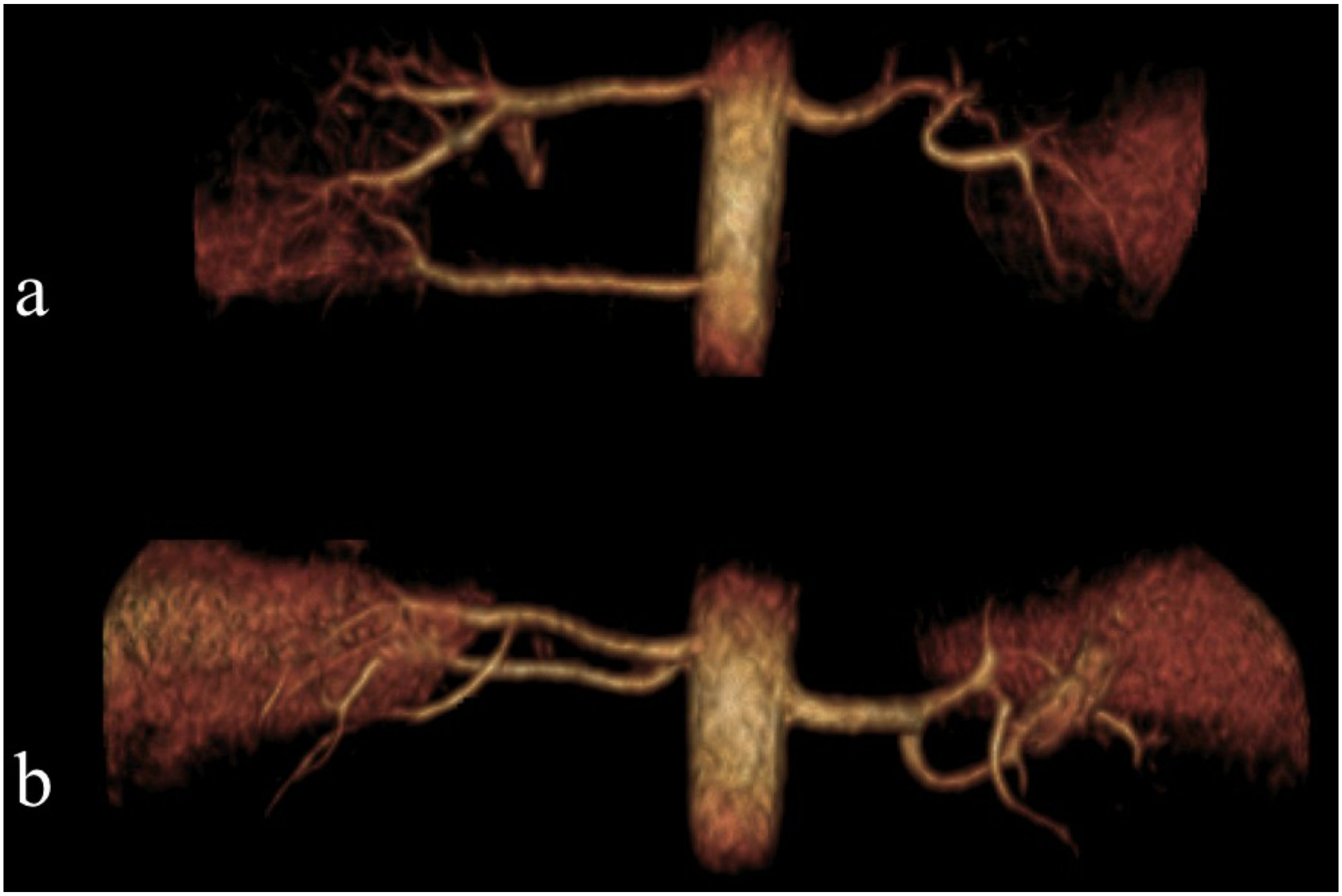

Figure 5.

Volume renderings of 22s breath-hold GUINNESS acquisitions from two healthy subjects demonstrating normal variant renal artery anatomy. In (a) there are two right renal arteries, and in (b) there is an early bifurcation of the right renal artery. Note the degree of blood-background contrast, fat and venous suppression and visualization of the renal vasculature, including small branch vessels.

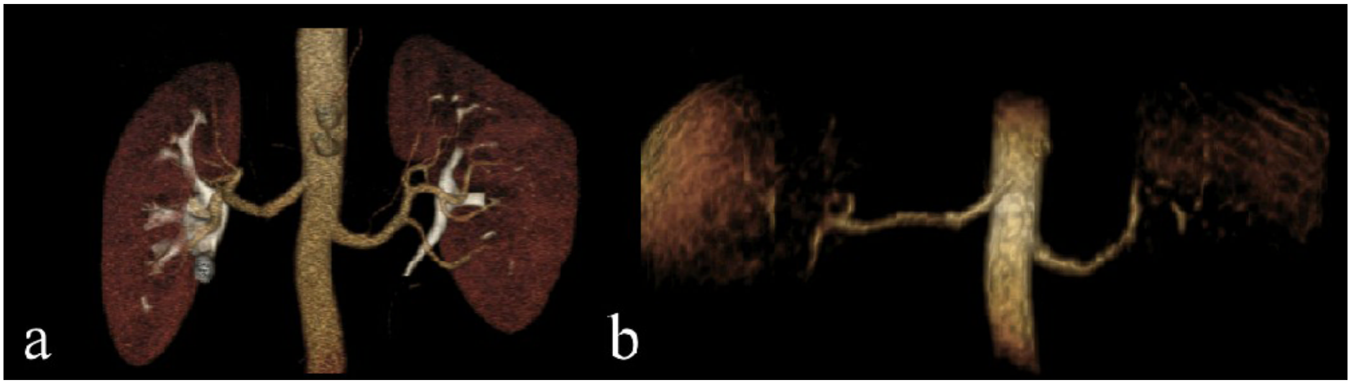

Figure 6.
Volume renderings of a conventional contrast-enhanced MRA scan acquired using a 3D SPGR sequence (a) and a 22s breath-hold GUINNESS acquisition (b) from a patient with fibromuscular dysplasia (FMD). Note the subtle beading of the right renal artery visibly in both images, and minimal involvement of the left main renal artery.

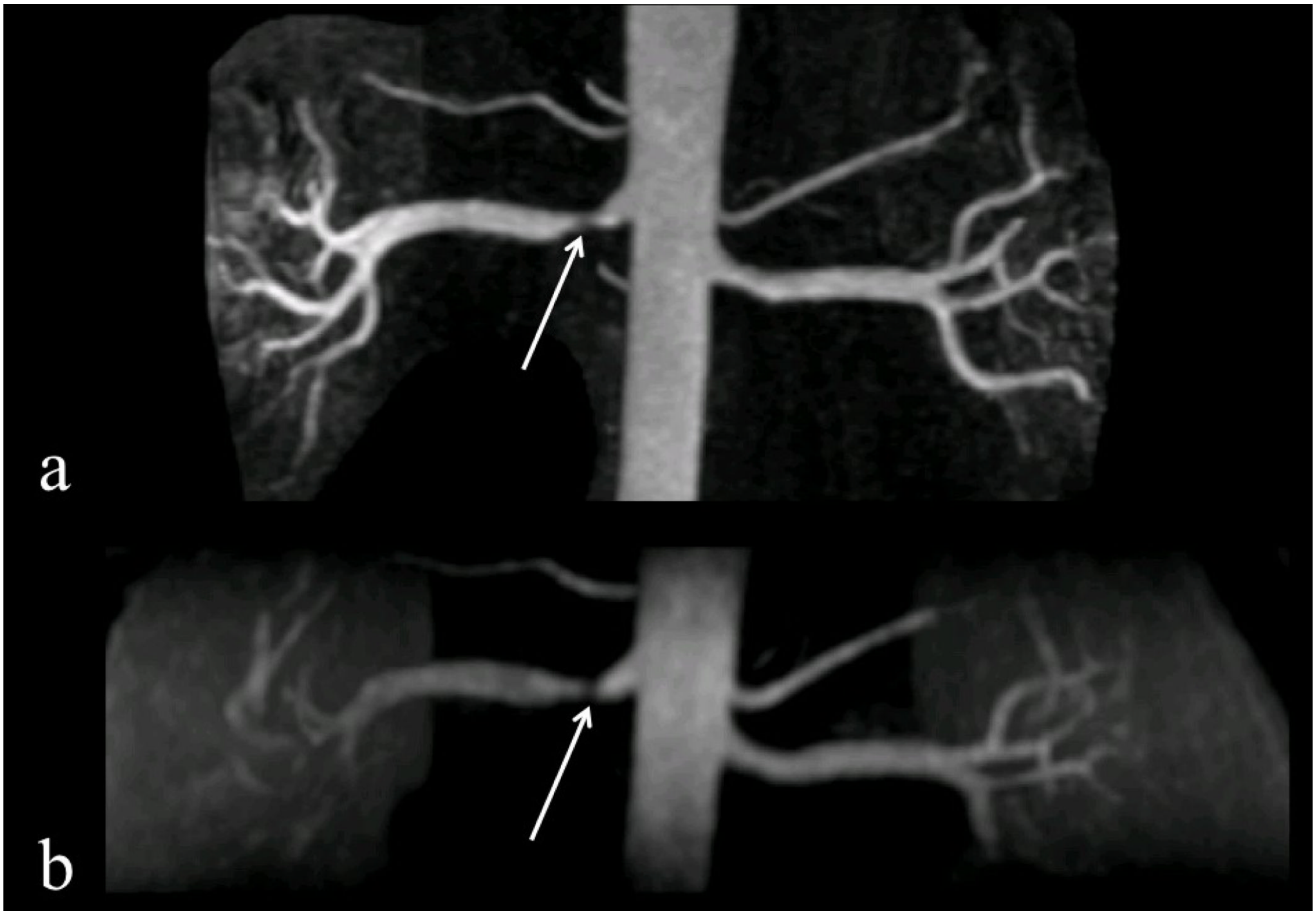

Figure 7.
Maximum intensity projections of a conventional contrast enhanced 3D MRA acquisition (a) and a 23s breath-hold GUINNESS acquisition (b) from a 51 year old patient with hypertension and mild renal insufficiency. There are two right and two left renal arteries bilaterally, with small superior accessory arteries on each side. Arrows highlight the stenosis in the right renal artery.