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Magnetic resonance angiography of fetal vasculature at 3.0 T

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Abstract

Magnetic resonance angiography has not been used much previously for visualizing fetal vessels in utero for reasons that include a contraindication for the use of exogenous contrast agents, maternal respiratory motion and fetal motion. In this work, we report the feasibility of using an appropriately modified clinical time-of-flight magnetic resonance imaging sequence for non-contrast angiography of human fetal and placental vessels at 3.0 T. Using this 2D angiography technique, it is possible to visualize fetal vascular networks in late pregnancy.

Keywords

Non-contrast magnetic resonance angiography; Time of flight vascular imaging; Placental vasculature; Fetal circulation; Pseudo-triggering

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Introduction

Imaging the placental and fetal vasculature is clinically important for early identification of vascular malformations and anomalous vascular development, especially in congenital heart disease [1–3]. Doppler imaging has been the mainstay for evaluating fetal vasculature with 3D/4D ultrasound (US) and spatiotemporal image correlation (STIC) [4–6]. However, issues related to limited US wave penetration in situations like maternal obesity, presence of bony structures, abnormal fetal position and oligohydramnios/anhydramnios could preclude proper US examination [7, 8]. In such cases, fetal magnetic resonance imaging (MRI) has served as a valuable adjunct to US imaging in obstetrics, especially for assessing the fetal central nervous system [9, 10]. However, the use of magnetic resonance angiography (MRA) for assessing fetal vasculature has been extremely limited, due to fetal motion, contraindication for use of exogenous contrast agents during pregnancy, maternal respiratory motion, requirement for high resolution and lack of a fetal heart-rate based physiological trigger signal required for some of the more advanced MRA techniques [11, 12]. Countering fetal motion requires fast data acquisition schemes and high resolution for visualizing the small-caliber vessels in the fetus. These are, however, competing goals in MRI due to limited available signal-to-noise ratio (SNR). Imaging at higher field strengths offers high SNR which could be leveraged for high resolution/fast imaging [13]. Imaging at the higher field of 3.0 Tesla (T), as opposed to conventional 1.5 T, could provide this higher SNR. Fetal imaging at 3.0 T has been previously reported, and recent studies have shown that it can be done safely with a very low specific absorption rate (SAR, a measure of the radio frequency (rf) energy deposition, defined as power absorbed per unit mass of the tissue, expressed in W/kg) [13, 14]. Quantitative MRI techniques, such as arterial spin labelling [15], phase contrast MRI [16], and susceptibility weighted imaging-based blood oximetry [17] that are increasingly being applied to the study of fetal physiology, often rely on localization of afferent and efferent vasculature of the organ. The fetal position in utero can be in various orientations, making the localization of the vessels of interest and ascertainment of their orientation important before application of these quantitative methods. Thus, fetoplacental MRA has an important role to play in the proper application of the above-mentioned quantitative MRI methods in the fetus. In this work, we report the feasibility of obtaining non-contrast MRA in third-trimester fetuses at 3.0 T that allows for 3D visualization the fetal vasculature.

Methods

Sequence optimization

Imaging parameters for the conventional 2D time-of-flight (TOF) angiography sequences were modified keeping in mind the: (a) expected range of physiological blood-flow velocities, (b) size of the vascular structures, (c) speed of acquisition and (d) specific absorption rate of the sequence. The mean blood-flow velocities in the umbilical vessels, the ductus venosus, aorta, inferior vena cava and fetal carotids are greater than 3 cm/sec [18] from 27 weeks on (third trimester). Considering these speeds, the theoretical vessel contrast as a function of flip angle was plotted for blood-flow velocities ranging from 3–30 cm/sec [18, 19], for 3.0 T and 1.5 T for a 2-mm thick slice and a repetition time (TR) of 22 ms (Fig.

1). A flip angle of 50° was chosen to ensure the enhancement of low velocities and to keep the SAR low. The diameter of the umbilical vessels, the major vessels of the heart and its branches including the carotids, is typically greater than 3 mm in the third trimester [20, 21]. Therefore, a voxel size of 0.4–0.7 mm isotropic (in-plane) was used so that vessels occupy 3–4 voxels or above. A field of view (FOV) of 400 × 400 mm was used to ensure general applicability, and a partial Fourier factor of 6/8 was used to reduce data acquisition time. The final sequence parameters of the 2D TOF for fetal MRA are provided in Table 1. Parameters of the conventional TOF are included for comparison. A saturation band was not used in order to keep the SAR low. The resultant fetal MRA sequence acquired one image/slice every 3–4 s (depending on the resolution used).

MRI data acquisition

The study was approved by the local Institutional Review Board and informed consent was obtained from all subjects before the MRI scan. As part of a larger ongoing study, the fetal/placental MRA data were acquired whenever the scan time permitted in third trimester subjects, and results from five subjects are presented here. The median and interquartile values for the subjects were 36 4/7 weeks and 1 day, respectively. All subjects had a normal US examination within 1 week prior to the MRI scan.

Fetal MRI was performed on a 3.0 T Siemens Verio system (Erlangen, Germany) using a four-channel body flex array and the spine coil. Routine anatomical scans using a 2D T2-weighted (HASTE) sequence were followed by the acquisition of the 2D fetal MRA sequence for imaging the fetal vessels. Placental and umbilical vessels were visualized when they were present in the imaging FOV. Whenever possible, the MRA was repeated to achieve appropriate coverage or when fetal motion was encountered. The MRI scan duration was limited to 60 min. Images containing significant motion were excluded, and image volumes were processed for vascular network visualization in 3D in VolView [22] (www.kitware.com). Two-dimensional maximum intensity projections (MIPs) were then created at the appropriate orientation from these 3D volumes. Videos of 3D reconstructions are provided in the Supplementary material.

Results

The great vessels of the fetal heart were clearly visualized (Fig. 2). Umbilical circulation with the umbilical arteries (UAs) joining the aorta and the umbilical vein joining the inferior vena cava was observed (Fig. 3). Fetal neck vessels, the common carotids arising from the subclavian branches of the aorta, the internal carotids joining to form the circle of Willis, the transverse sinus, jugular veins and the vertebral arteries joining to form the basilar artery were clearly visualized in a 36-week and 4-day fetus (Fig. 4). Intracranial vessels such as the superior sagittal sinus, transverse sinus and the middle cerebral artery (all in the order of 1.5–2 mm in diameter), were visualized and reconstructed in the 3D view. Chorionic vessels of the placenta as well as the vessels on the maternal side were also visualized (Fig. 5&6). The SAR of the MRA as well as that of the HASTE sequence were <0.25 W/Kg and 0.9 W/Kg, respectively.

Discussion

These results show that 2D TOF MRA can indeed provide an excellent depiction of fetal and placental vasculature, at 3.0 T. In many cases, minimal fetal motion allowed for the successful production of high quality 3D reconstructions despite the lack of maternal breath-hold. This may be largely due to the rough synchronization of the per-slice imaging time of 3.5–4 s with the typical maternal respiration rate, effectively leading to pseudo respiratory gating [23]. The relatively long TR helped in reducing the SAR while increasing the blood signal due to a higher inflow effect. Because of the high flow velocities in the fetus and placenta, using a similarly long TR and thin slice thickness, it may be possible to obtain such a high quality MRA of the fetus in the third trimester at 1.5 T as well as suggested by Fig. 1.

A major advantage of MRA relative to US is its larger FOV. This provides a global perspective of the vascular network of the mother and fetus in relation to the other anatomical structures and is helpful for the identification of syndromic vascular malformations such as Klippel-Trenauny, Hereditary Hemorrhagic Telangiectasia (AKA Osler-Weber-Rendu), etc. In these cases, vascular malformations may be located anywhere in the fetus, so a larger viewing window is advantageous for improved sensitivity over US as a screening modality. High-resolution MRI helps in the visualization of small fetal vessels, particularly in the head and neck, which are difficult to visualize with US due to the presence of the skull. A larger FOV also helps in the global evaluation of the placental vasculature, and higher resolution allows for evaluation of the chorionic surface vessels. Recent works have indicated that chorionic vessel density/distribution may be an important indicator of placental health [24, 25]. Thus, placental MRA may also have an important role to play in this assessment, especially in the second and third trimesters [26].

There are a few limitations in this work. The technique was not applied in the same fetal anatomical location consistently. Furthermore, the technique was applied with variable volume coverage due to scan-time restrictions, which precluded systematic analysis of the success rate of the technique. Systematic assessment of the diagnostic utility will be the focus of our future work. Nevertheless, the current report is the first step in showing the potential of the TOF MRA technique for visualizing fetal vasculature in utero using MRI. Faster scanning speeds may be achieved using non-Cartesian sampling such as radial/spiral combined with compressed sensing [27–29]. These trajectories are naturally insensitive to motion and amenable to motion correction [30] and thus may improve the robustness of the technique for application in the second trimester. Combined with parallel imaging, these methods may accelerate data acquisition and/or improve SNR.

In conclusion, we report that 3D reconstruction and visualization of fetal vasculature using 2D TOF MRA data at 3.0 T is viable in a clinical setting.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Key Points

- 3D-visualization of fetal vasculature is feasible using non-contrast MRA at 3.0 T.
- Visualization of placental vasculature is also possible with this method.
- Fetal MRA can serve as a vascular localizer for quantitative MRI studies.
- This method can be extended to 1.5 T.

Fig. 1.

Theoretical contrast between the blood and background tissue versus flip angle for blood velocities of 3 and 30 cm/sec. Experimental conditions; TR = 22 ms; TE = 5 msec; T1 of blood [31, 32] = 1,890 ms (3.0 T), 1,400 (1.5 T); T1 of background tissue [33, 34] = 2,500 ms (3.0 T), 1,700 (1.5 T), spin density of blood and background [35] 0.82 and 0.83 (arbitrary units), T2* of blood at 1.5 T & 3.0 T and background tissue [34, 36, 37] = 72.4 & 199/200 ms. A flip angle of 50° was used to ensure enhancement at low velocities while maintaining a low specific absorption rate (SAR). Almost identical curves for 3.0 T and 1.5 T indicate that similar data may be acquired at 1.5 T as well, using these parameters

Fig. 2. (A) Two-dimensional TOF MRA image showing the fetus in the head-down position with the fetal heart clearly visible. (B) Maximum intensity projection obtained from the 3D vascular volume reconstructed from the 2D TOF data (shown in A). The fetal heart and its major vessels are visualized (gestational age – 37 weeks). *IVC* inferior vena cava, *PV* portal vein, *CCA* common carotid artery

Fig. 3. Visualization of the umbilical-fetal circulation. **(A, B)** Orthogonal views of the umbilical-fetal vasculature maximum intensity projections (MIPs) (gestational age – 36 weeks 4 days) showing the umbilical arteries joining branches of the descending aorta and the umbilical vein joining the DV. **C** anatomical image showing the orientation of the fetal position, *IVC* inferior vena cava, *UV* umbilical vein, *UA* umbilical artery, *IA* iliac artery, *DV* ductus venosus

Fig. 4.

Coronal (A) and sagittal (B) maximum intensity projection (MIP) views of the fetal head and neck vessels. (C) A single 2D slice from the time-of-flight MRA volume from which the 3D MIPs were generated (gestational age – 36 weeks 4 days). *SSS* superior sagittal sinus, *ICV* internal cerebral vein, *VoG* vein of galen, *SS* straight sinus, *MCA* middle cerebral artery, *TS* transverse sinus, *ICA* internal carotid artery, *BA* basilar artery, *VA* vertebral artery, *CCA* common carotid artery, *IJV* internal jugular vein, *SCV* subclavian vein

Fig. 5.
(**A, B**) Basal plate vasculature on the maternal side of the placenta. (**C, D**) T2 HASTE images showing the volume covered for the MRA scan for (**A**) and (**B**), respectively. The arrow head indicates basal plate vessels on the uterine side of the placenta (**A, C**: gestational age – 36 weeks 4 days; **B, D**: gestational age – 36 weeks 5 days)

Fig. 6.
(**A, B, C**) MRA of the placental chorionic plate vessels. Primary and secondary branches of the chorionic plate vessels (*arrow heads*) are visualized. (**D, E**) Corresponding anatomical images showing the volume covered in the MRA acquisition. (**A, D**: gestational age – 36 weeks 4 days; **B, C, E**: gestational age – 37 weeks)

Table 1

Sequence parameters for 2D fetal MRA contrasted against the conventional 3D time-of-flight MRA sequence used in adult imaging

	Mode	TE (ms)	TR (ms)	Reconstructed resolution (mm ³)	FA (degree)	BW (Hz/pixel)	# Slices	Acq. time (min)	Parallel imaging
Conventional	3D	3.4–11.3	25	(0.75–1) × (0.75–1) × (1.5–2)	20	42	50–70	5–7	2
Fetal MRA	2D	4.92	22	(0.4–0.7) × (0.4–0.7) × (1.5–2)	50	241	26–64	2–5	2

TE echo time; *TR* repetition time; *FA* flip angle; *BW* bandwidth