

FETAL MAGNETIC RESONANCE IMAGING

Jaladhar Neelavalli, PhD and E. Mark Haacke, PhD
Department of Radiology, Wayne State University

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Dr. Edgar Hernandez-Andrade,
PRB

Dr. Lami Yeo
PRB

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PRB

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Staff at the Wayne State Univ. MR Research Facility

*And...to all the mothers who have participated and continue to
participate in our studies*

FETAL IMAGING TO DATE

192 normal + 41 clinical cases with gestational ages ranging from 20 weeks to 38 weeks were collected up to 1st January 2017.

Sequences	# of Cases acquired	
	Normal	Clinical
T2 Haste	192	41
T1 (2D &/ 3D)	171	33
SWI (2D &/ 3D/Zoom SWI)	170	33
MRS (Spectroscopy)	90	20
DWI/ZoomDTI (ADC maps)	54	12
Umbilical Flow (Average)	106	21
MRA	113	30
Radial SWI	24	2
Radial MRA	29	3
Radial Time Resolved	5	2

A detailed MR protocol is available for all these sequences.

ANATOMICAL IMAGING SEQUENCES

T₂ Weighted Contrast – 2D

T₂ – HASTE at 3.0T

- Fluids are bright on T₂W images
- Shows good contrast between cortex and the developing white matter
- Roughly 1-2 secs/image

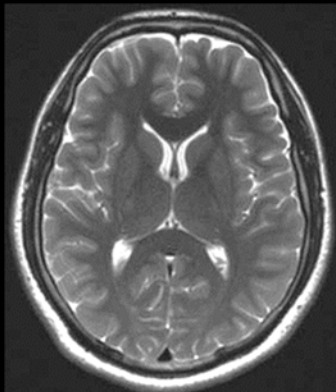
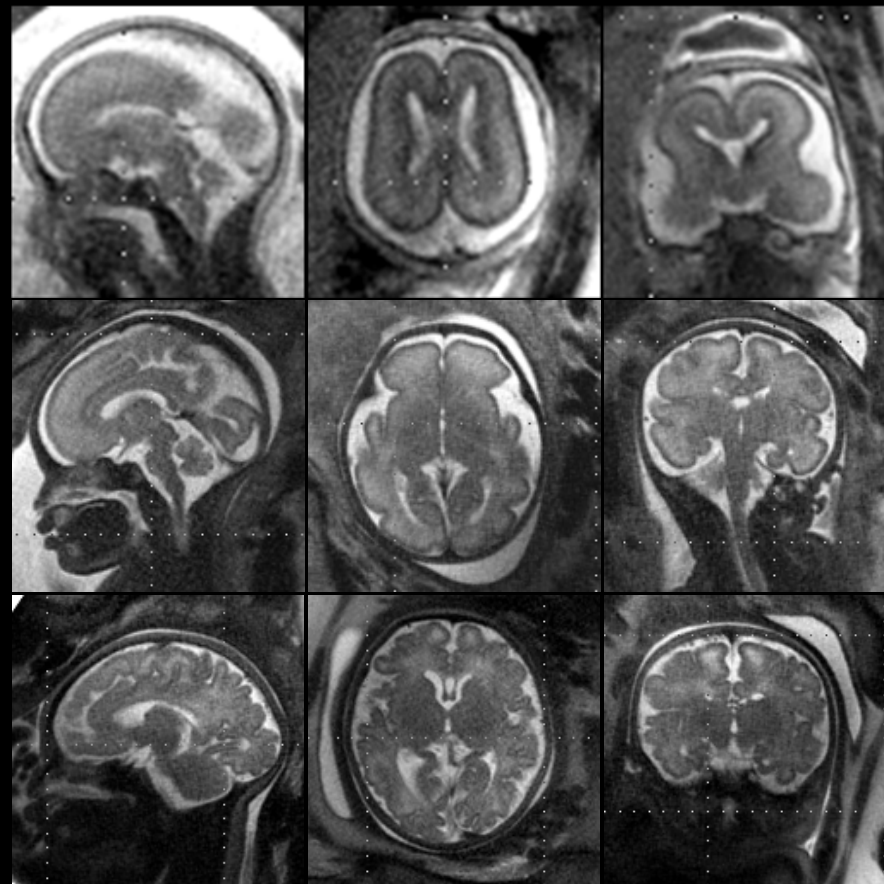


Image from an Adult Brain



20 5/7 weeks

30 4/7 weeks

36 6/7 weeks

Voxel Size – 0.9×0.9×3.0 mm³; Acq. Time – 3.5 secs/slice

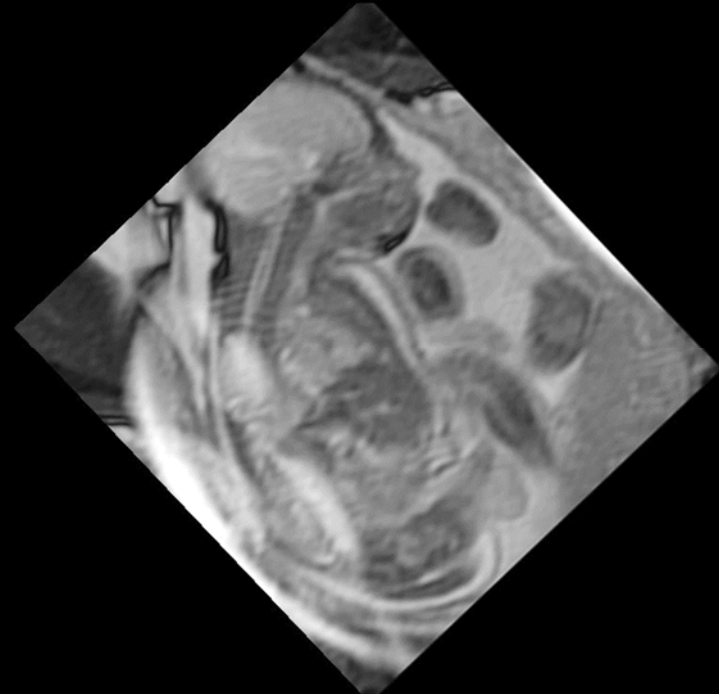
Krishnamurthy, U., Neelavalli, J., Mody, S., Yeo, L., Jella, P. K., Saleem, S., ... & Katkuri, Y. (2015). MR imaging of the fetal brain at 1.5 T and 3.0 T field strengths: comparing specific absorption rate (SAR) and image quality. *Journal of perinatal medicine*, 43(2), 209-220.

ANATOMICAL IMAGING SEQUENCES

T₂ Weighted Contrast – 2D

SSFP – roughly 500 msecs per image

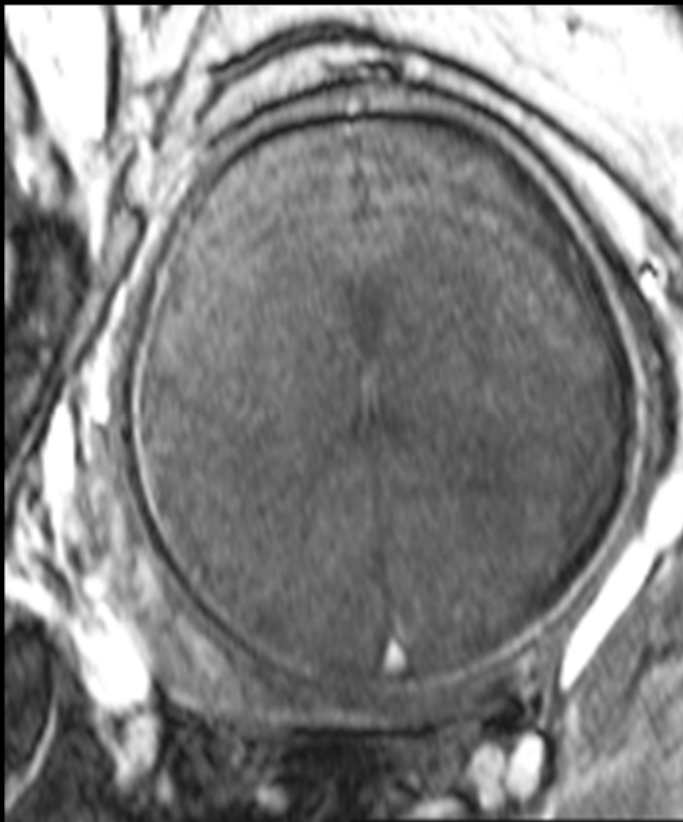
- Often used to visualize fetal movements due to its speed of acquisition
- Good for quick overall fetal visualization



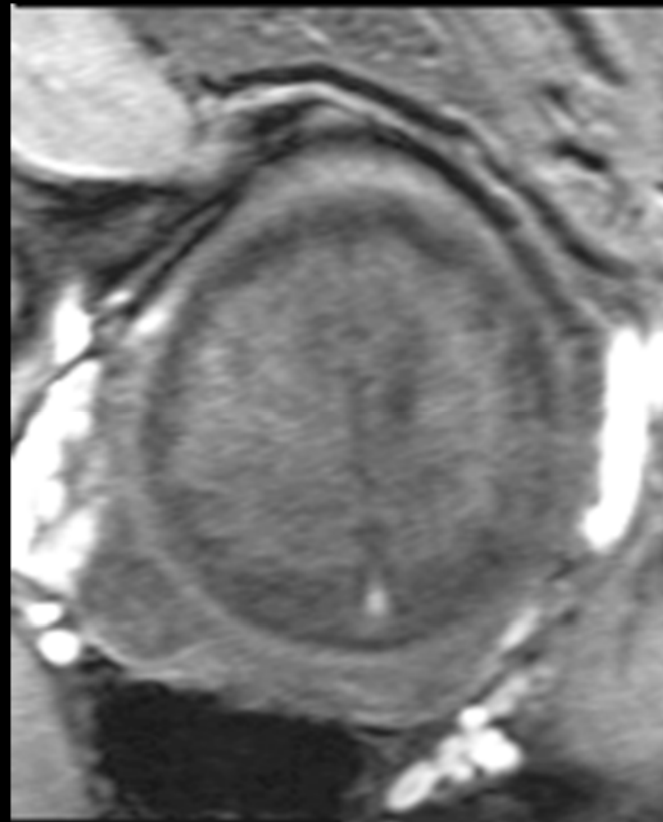
ANATOMICAL IMAGING SEQUENCES

T₁ Weighted Contrast

2D



3D



GA = 35 1/7 weeks

Voxel Size – 1.4 x 0.7 x 3.5 mm³; Acq. time – 23 to 28 secs

WSU/PRB

CONVENTIONAL IMAGING SEQUENCES

MR Spectroscopy

Brain metabolites typically measured using MRS:

Choline – marker of cell membrane stability and myelination (3.2ppm)

NAA – neuronal or axonal marker (2.0ppm)

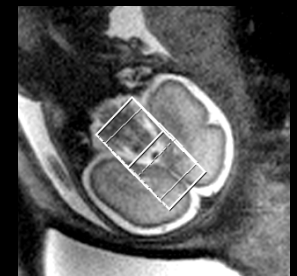
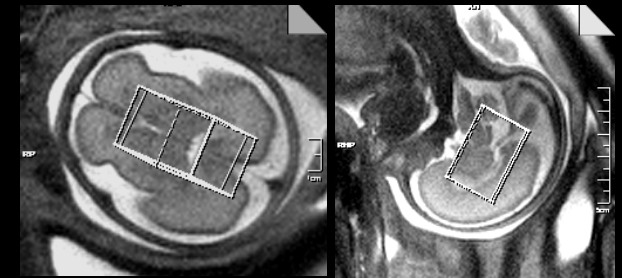
Creatine – marker of metabolic activity (3.0ppm)

Lactate – marker of metabolic acidosis (1.3ppm)

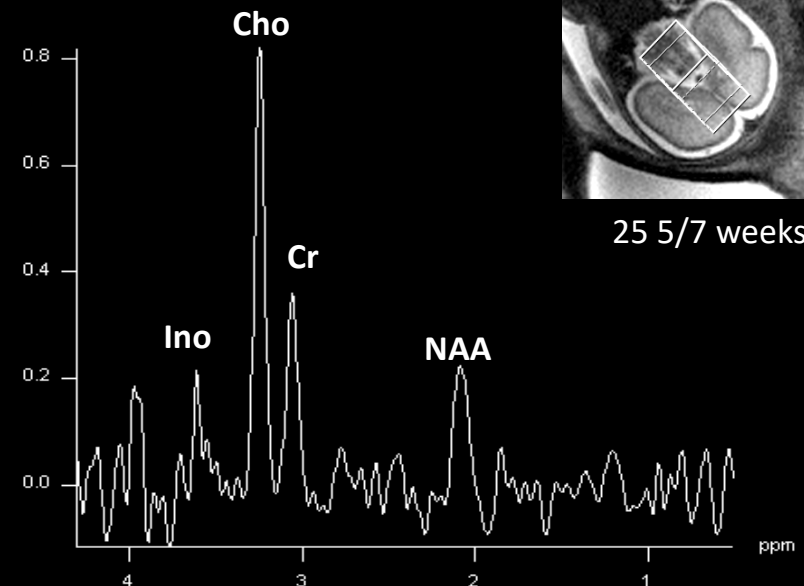
Myoinositol – marker of lipid synthesis (3.5ppm)

(Other metabolites – glutamate, glutamine)

Normal Fetus



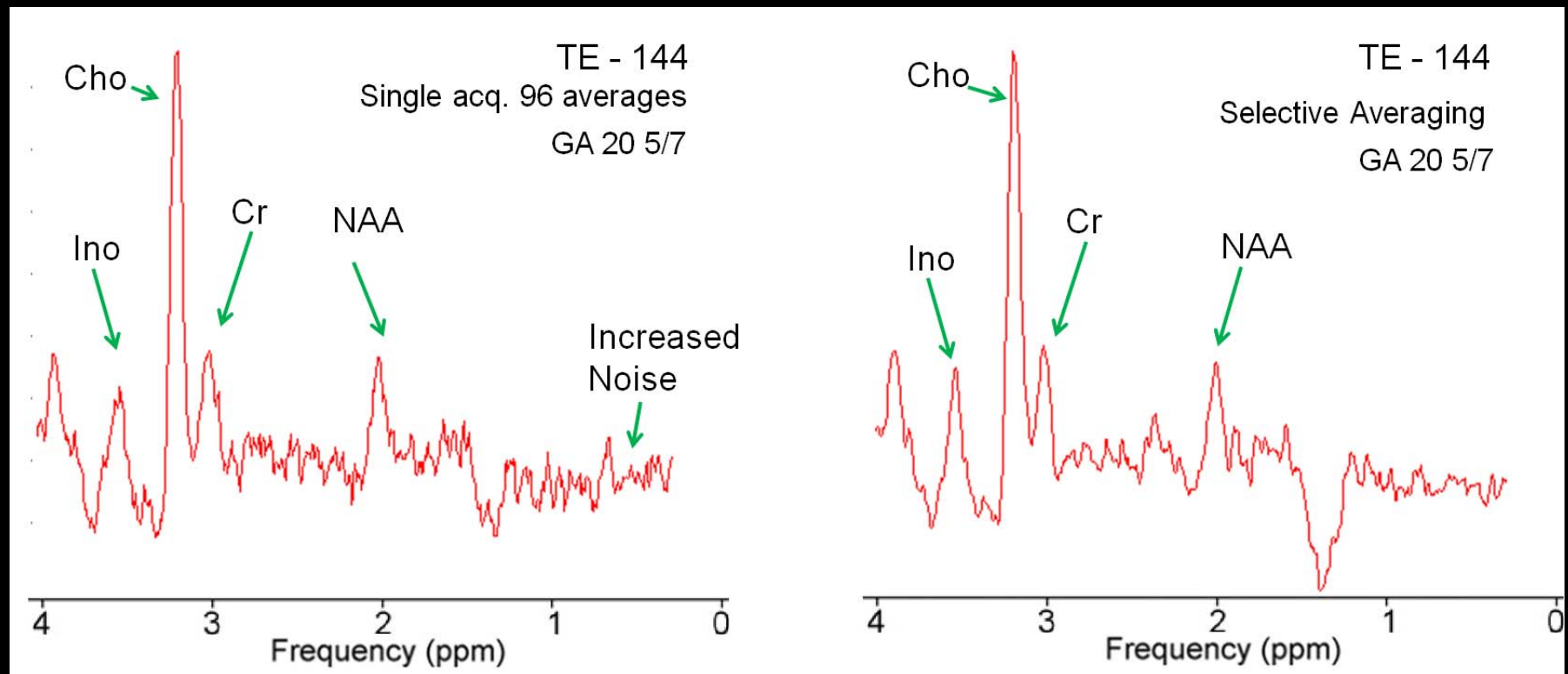
25 5/7 weeks



CONVENTIONAL IMAGING SEQUENCES

MR Spectroscopy

Full averaging (96) versus selective averaging through multiple measurements (6 x 16)



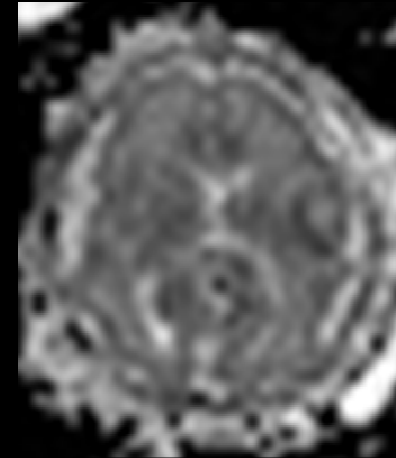
CONVENTIONAL IMAGING SEQUENCES

Diffusion Weighted Image (DWI)

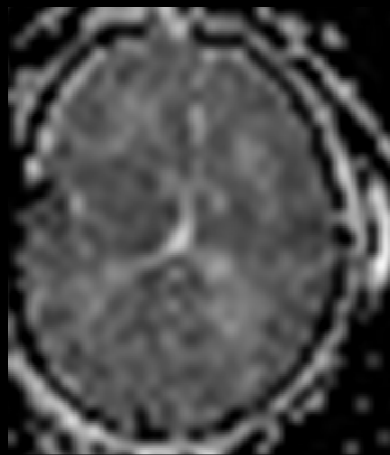
27 2/7
weeks



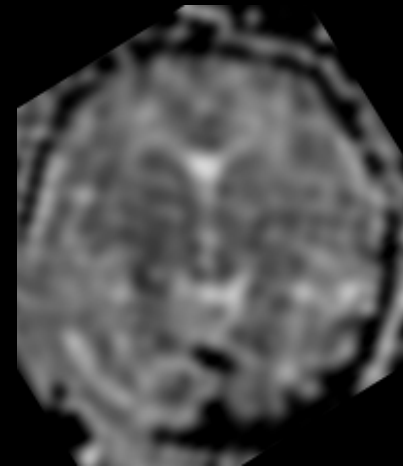
30 4/7
weeks



38 2/7
weeks



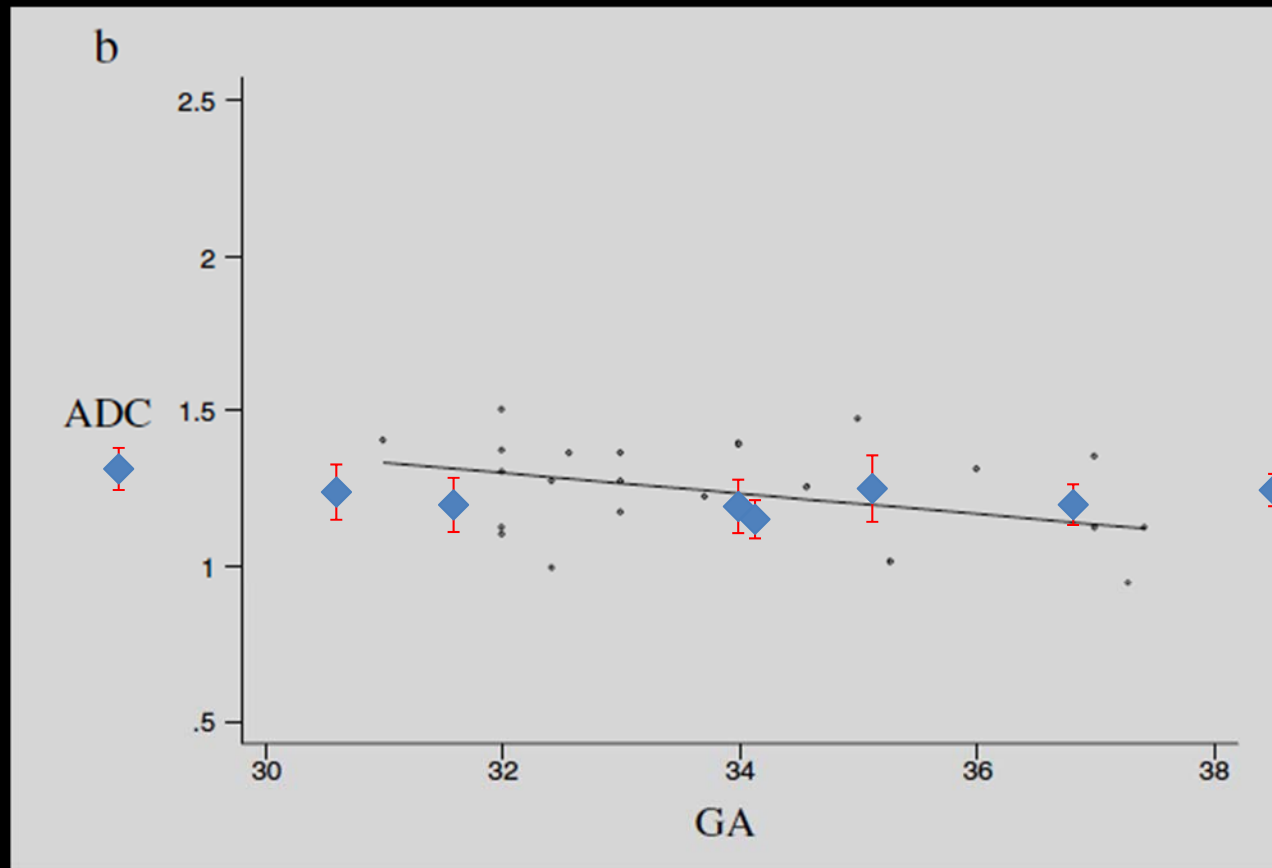
34 1/7
weeks



Voxel size – $3.0 \times 3.0 \times 3.0 \text{ mm}^3$; Acq. time – 1 min; b – 0, 500-700 s/mm^2

CONVENTIONAL IMAGING SEQUENCES

Corpus Callosum ADC



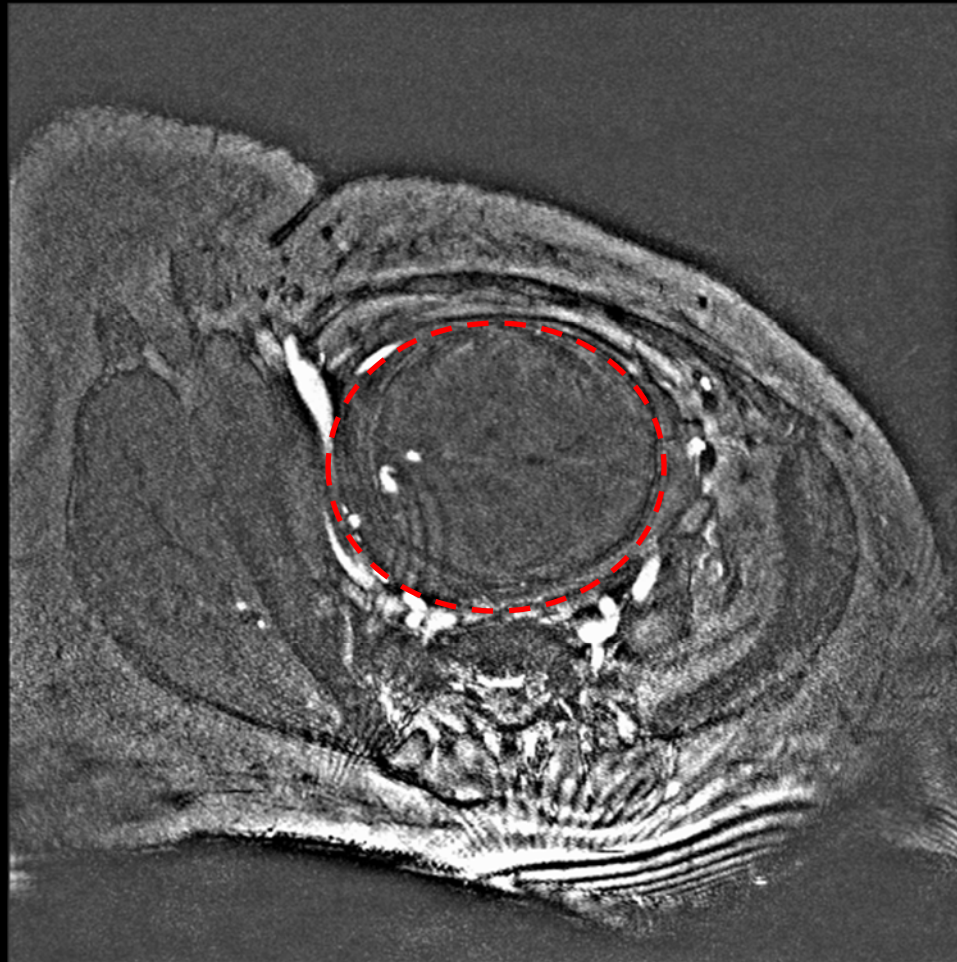
Our data – $1.2 \text{ } \mu\text{m}^2/\text{ms}$

Literature Value – $1.3 \pm 0.07 \text{ } \mu\text{m}^2/\text{ms}$

Bui, Tony, et al. "Microstructural development of human brain assessed in utero by diffusion tensor imaging." *Pediatric radiology* 36.11 (2006): 1133-1140.

CONVENTIONAL IMAGING SEQUENCES

MRA – 3D - Time of Flight Angiography



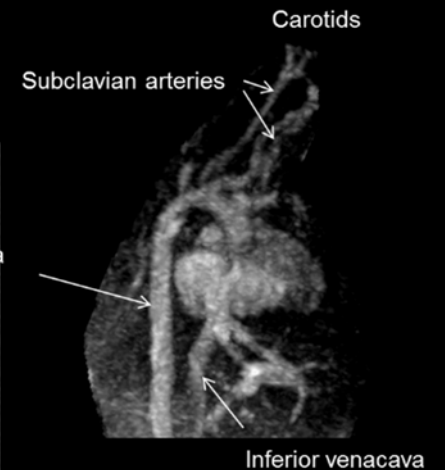
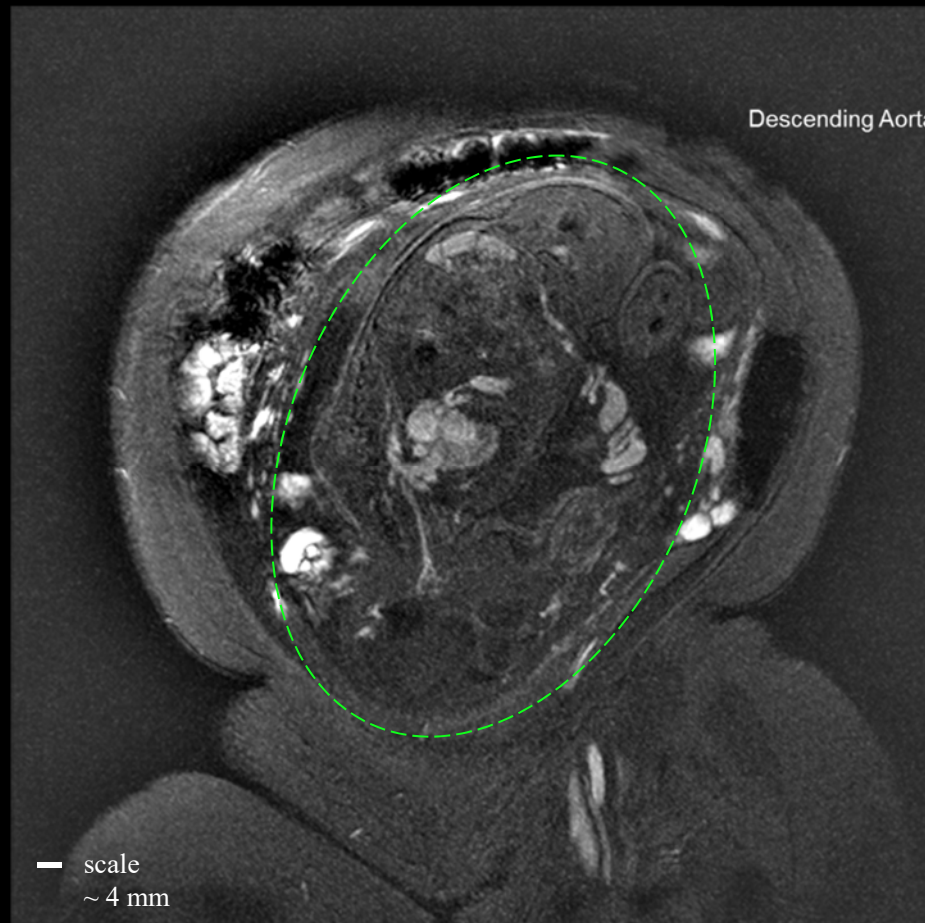
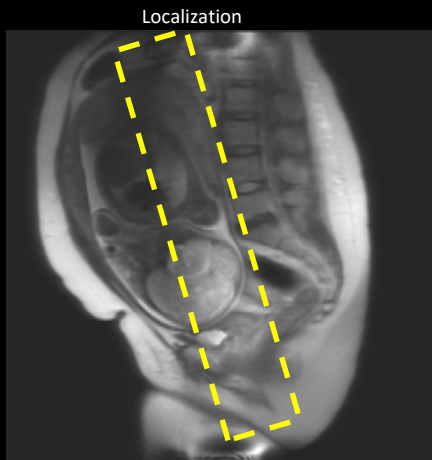
Voxel Size – $0.7 \times 0.7 \times 1.2 \text{ mm}^3$

Acq. Time - 28 s

CONVENTIONAL IMAGING SEQUENCES

MR angiography in the Human Fetus: Fetal Heart

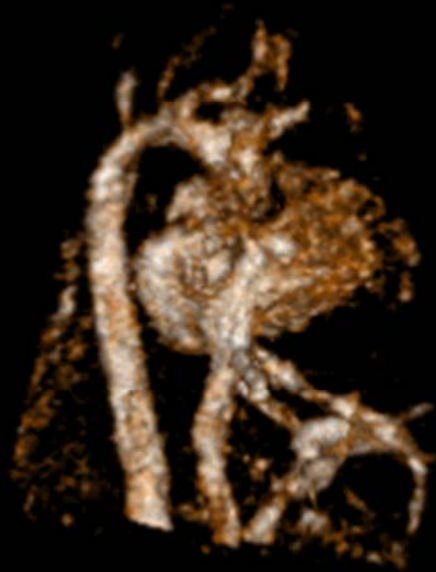
GA 37 weeks



Neelavalli, J., Krishnamurthy, U., Jella, P. K., Mody, S. S., Yadav, B. K., Hendershot, K., ... & Hassan, S. S. (2016). Magnetic resonance angiography of fetal vasculature at 3.0 T. *European radiology*, 26(12), 4570-4576.

CONVENTIONAL IMAGING SEQUENCES

MRA in the Human Fetus: Fetal Heart

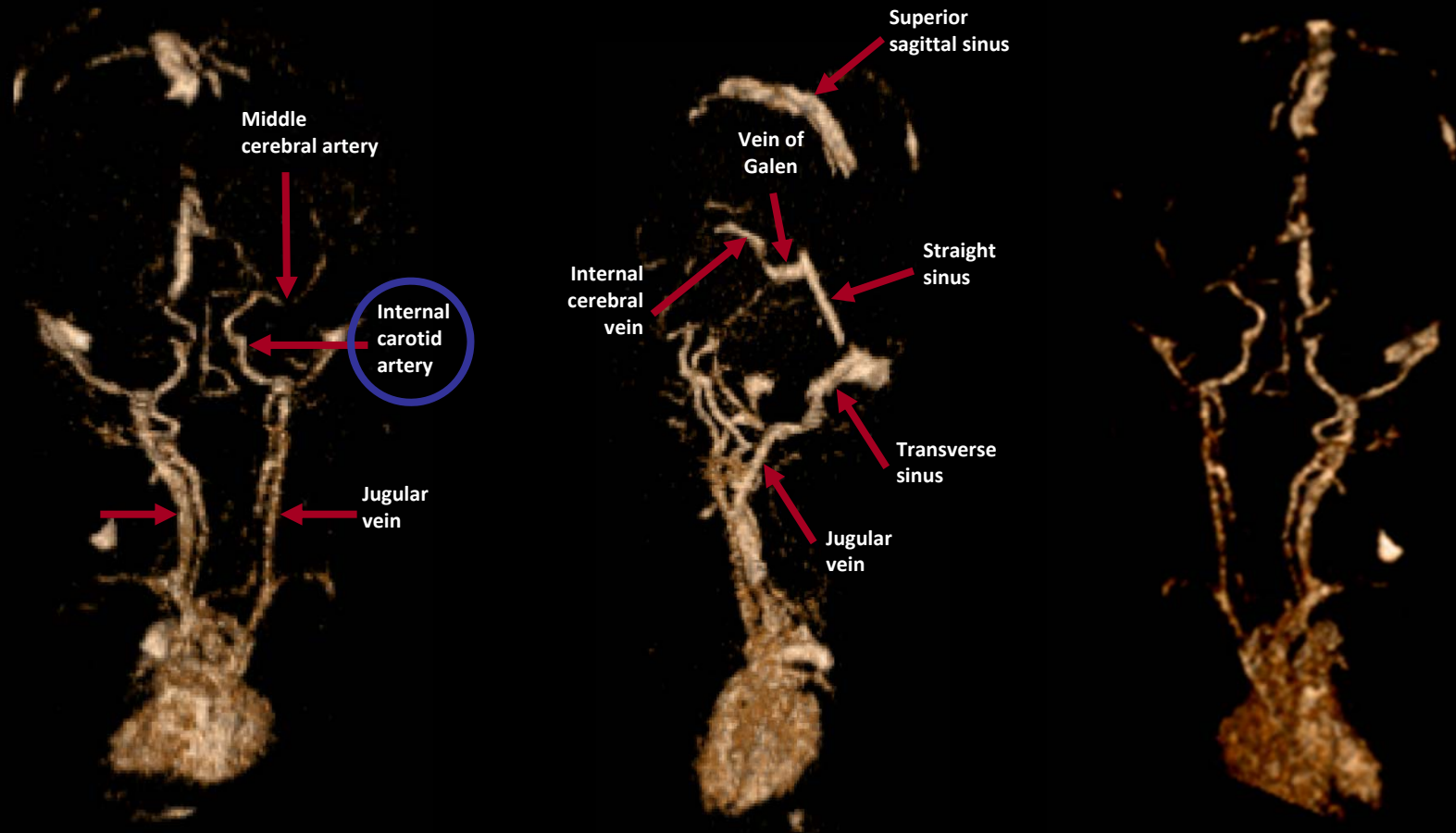


— scale
~ 4 mm

GA – 37 weeks

CONVENTIONAL IMAGING SEQUENCES

MRA in the Human Fetus: Head and Neck

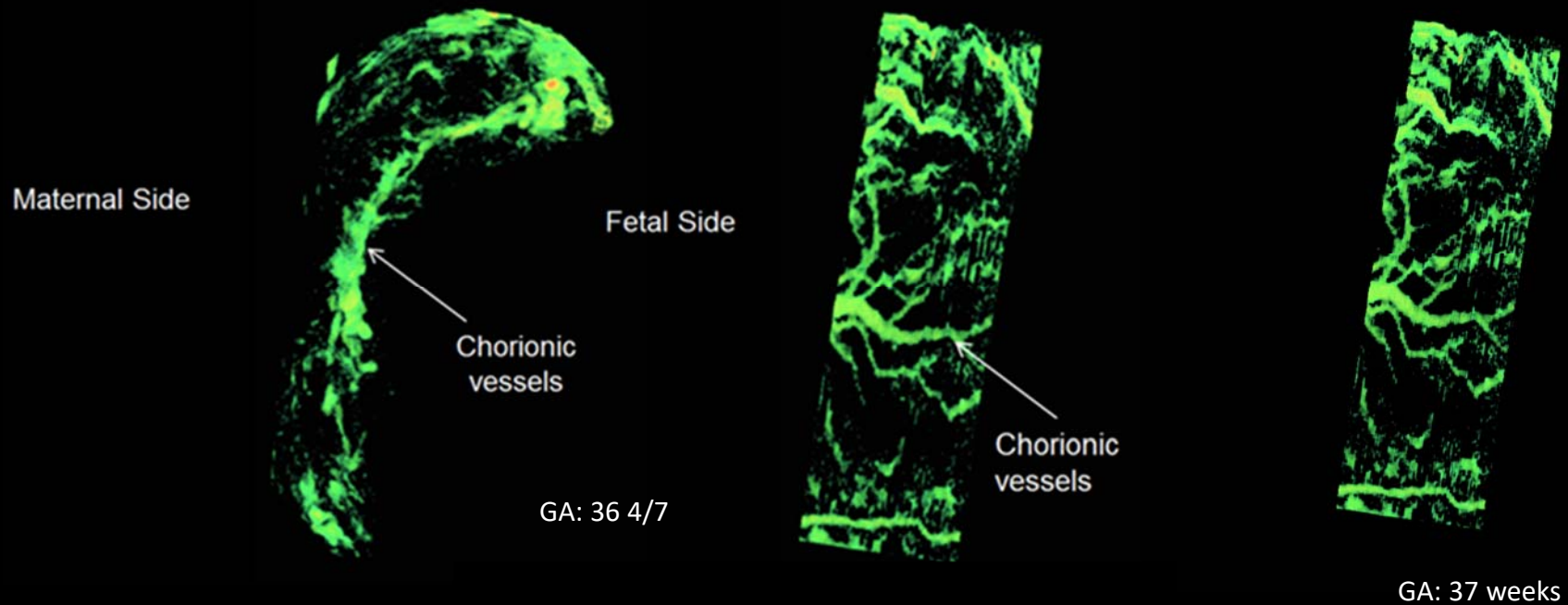


GA - 36 4/7 weeks

Neelavalli, J., Krishnamurthy, U., Jella, P. K., Mody, S. S., Yadav, B. K., Hendershot, K., ... & Hassan, S. S. (2016). Magnetic resonance angiography of fetal vasculature at 3.0 T. *European radiology*, 26(12), 4570-4576.

CONVENTIONAL IMAGING SEQUENCES

Placental MRA: Chorionic Vessels

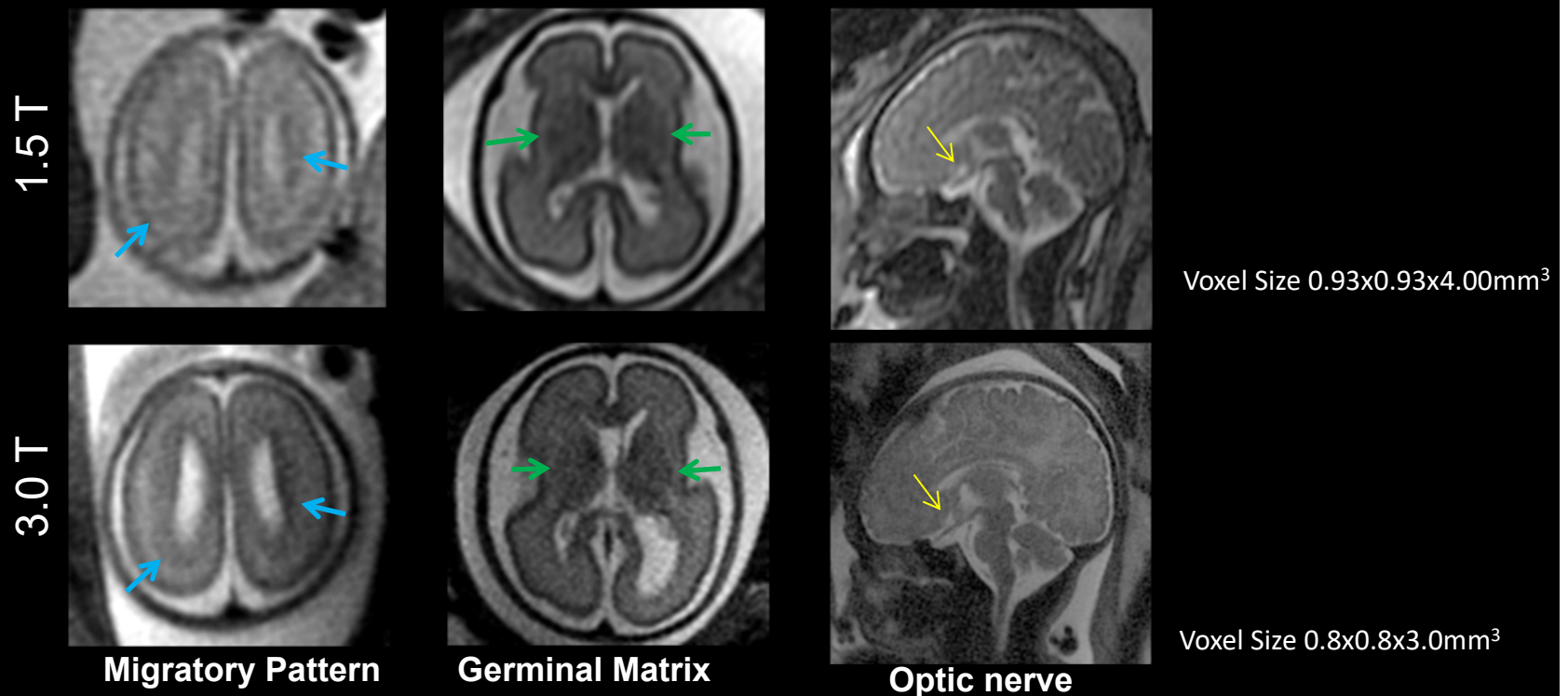


FETAL MRI – IMAGING FIELD STRENGTH

- Clinically fetal MRI has been performed at **1.5 Tesla** field strength
- However, imaging at higher field strengths (**3.0 Tesla**) has several advantages...
 - o Better image quality
 - o Higher resolution imaging
 - o Increased sensitivity to metabolites (spectroscopy)

FETAL IMAGING AT 3 TESLA

Higher resolution @ 3T affords better visualization of anatomy

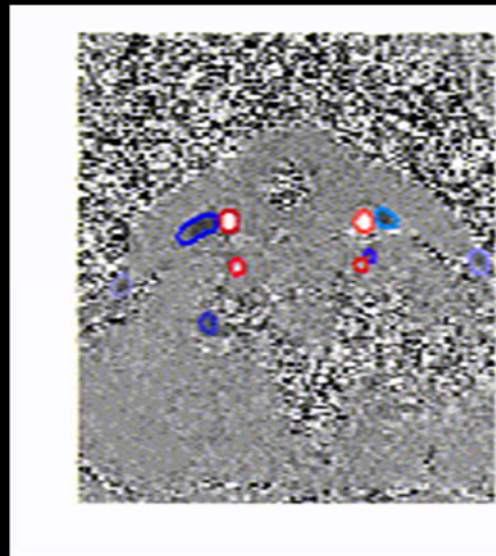


Krishnamurthy, U., Neelavalli, J., Mody, S., Yeo, L., Jella, P. K., Saleem, S., ... & Katkuri, Y. (2015). MR imaging of the fetal brain at 1.5 T and 3.0 T field strengths: comparing specific absorption rate (SAR) and image quality. *Journal of perinatal medicine*, 43(2), 209-220.

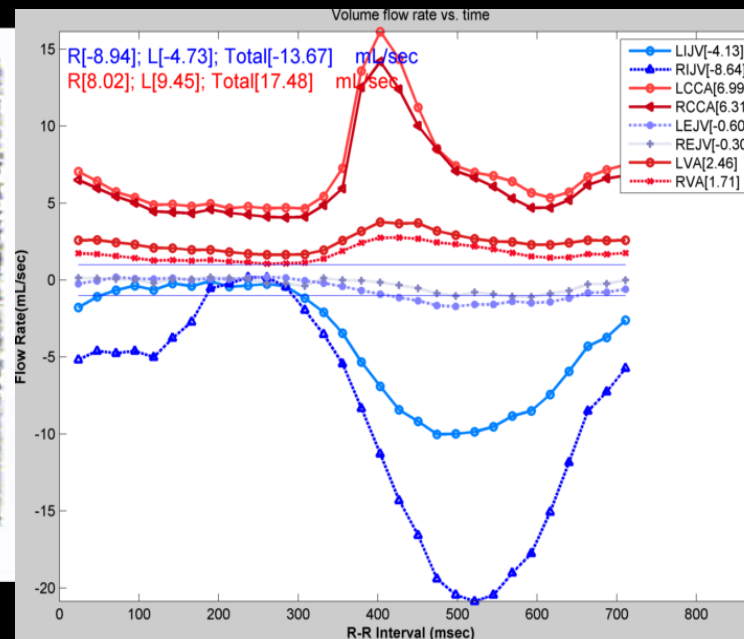
NEW IMAGING METHODS

Phase Contrast MRI (PC-MRI)

- Sensitizes MRI phase measurement to blood flow velocity
- Considered gold standard for in vivo volume-flowrate measurements



Flow through the neck in an adult

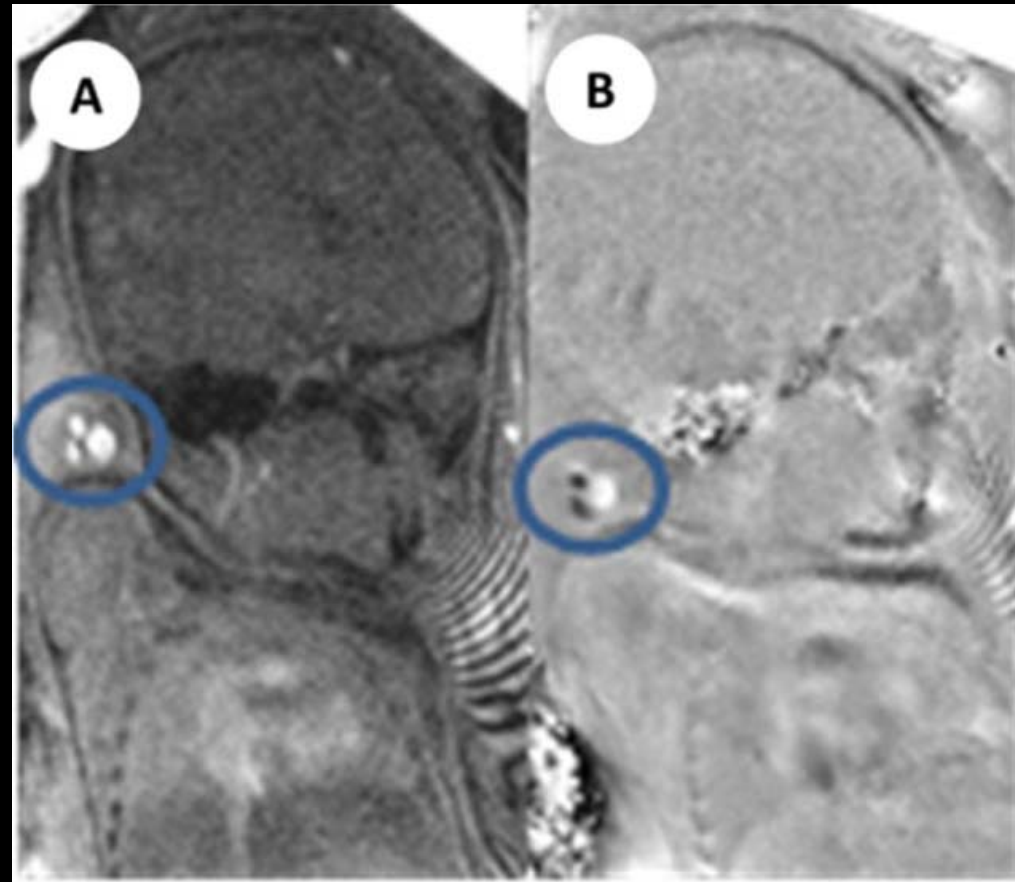


NEW IMAGING METHODS

Results for non-triggered PC

Voxel Size -
 $0.7 \times 0.7 \times 4.0 \text{ mm}^3$

Acquisition time
75 secs
(from 6 sets of
two 6 sec scans)

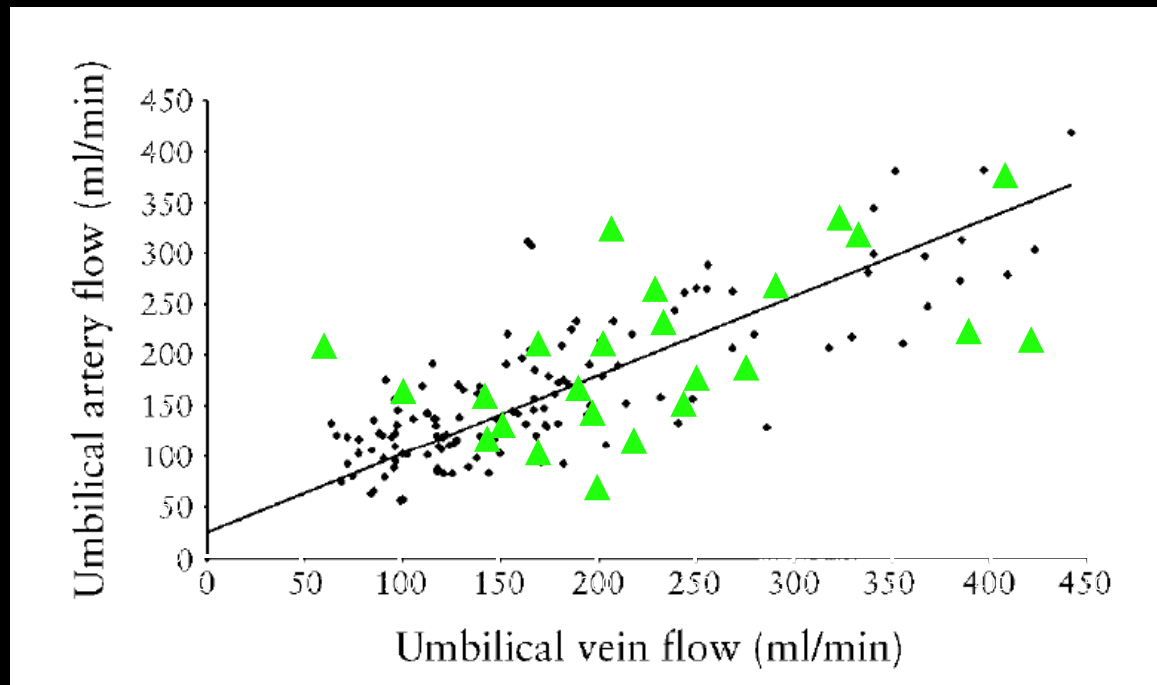


Magnitude

Phase

35 1/7 weeks

Comparison between US and MRI

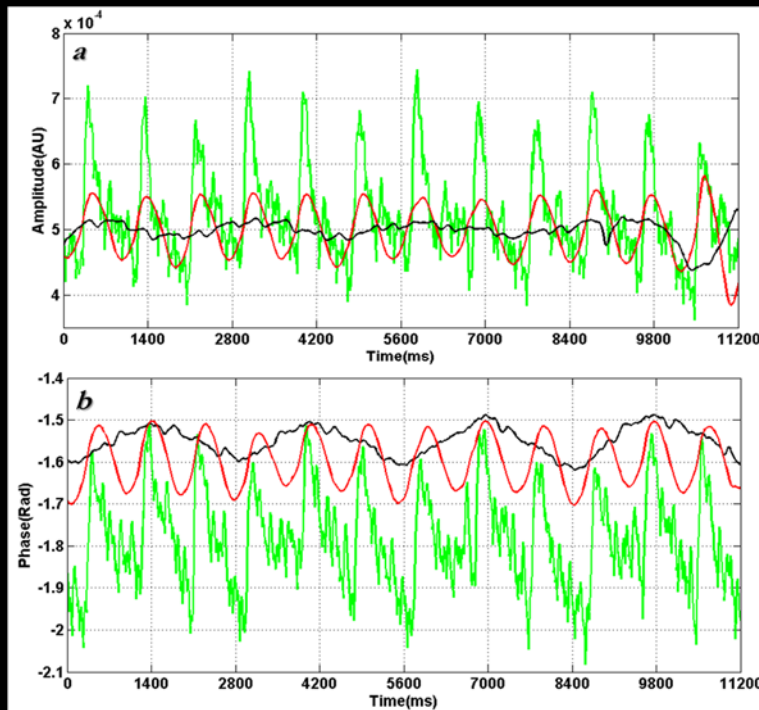


Our measurements in green overlaid on the reference plot from [1]

[1] Lees, C., Nikolaides et al. Assessment of umbilical arterial and venous flow using color Doppler. *UOG* 1999;14:250–255

SELF GATING

Can we obtain ECG information from over-collecting the data without gating?



No self-gating

Systole

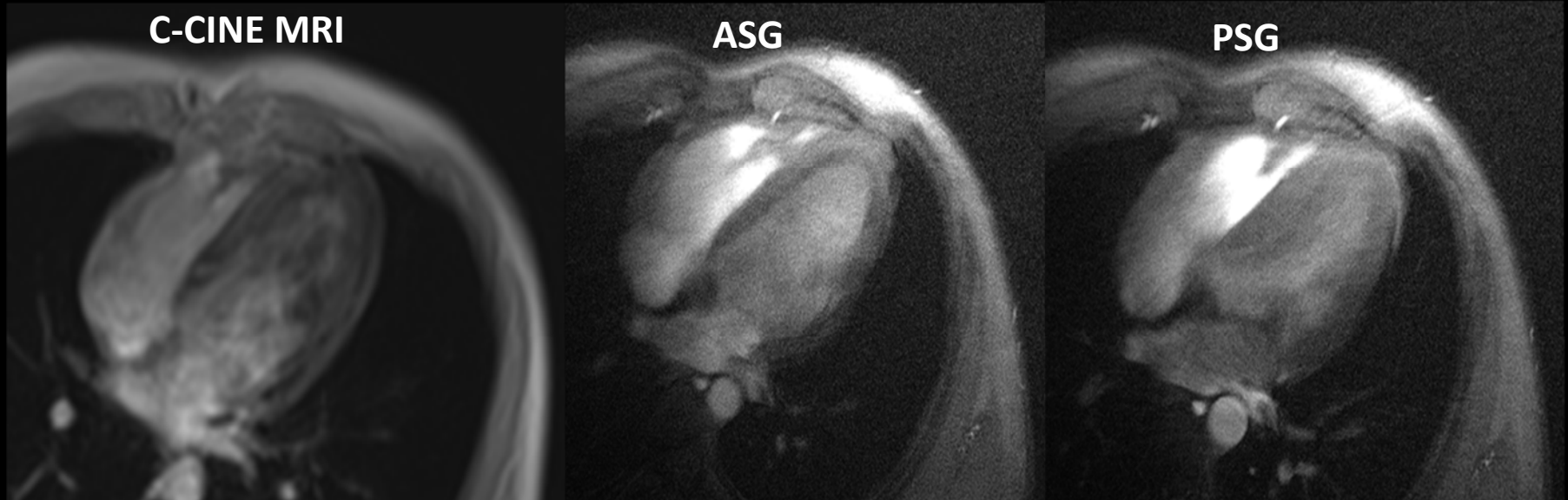
Diastole



- a. Central k-space amplitude self-gating signal (ASG)
 - b. Central k-space phase self-gating signal (PSG)
- Central k-space signal; Respiratory self-gating signal in black and Cardiac self-gating signal

Adult Heart

RECONSTRUCTION IMAGE: ADULT DATA



Comparison between CINE and Radial MRI:
13 cardiac phases are reconstructed by each approach

**C-CINE MRI
requires a
breathhold**

Sequence	Resolution (mm)	Scan Time (/slice)
CINE	2.2x1.8x8	15s
Radial	0.5x0.5x8	2.8min

MOTIVATION FOR RADIAL MRA

- General Advantages of Radial
 - Easy to obtain larger FOV (Needed for fetal imaging)
 - Easy to image at higher resolution (fetal brain is small)
 - Motion robustness
 - Easy to incorporate with Compressed Sensing
- Long TR for fetal imaging, can be used to collect dual echo data. This can be used for
 - Reduces SAR concerns
 - T_2^* mapping of the fetal vasculature
 - enhancement of the SNR averaging the echoes
 - SWI can be obtained from the second echo

RADIAL SAMPLING APPROACH:

Motion resistant fetal MR angiography

Cartesian Sampling
(0.7x0.7x2.0mm³)



The data corruption from motion, which appears as streaks (green arrows) and broken vessels in the left image (Cartesian) are absent in the image on the right (Radial).

Future directions to speed up imaging includes using compressed sensing (CS).

Total acquisition time 4 seconds/slice and 64 slices. Current CS methods can increase speed by a factor of 6 clinically.

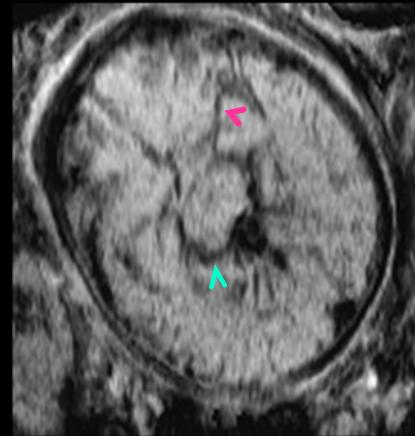
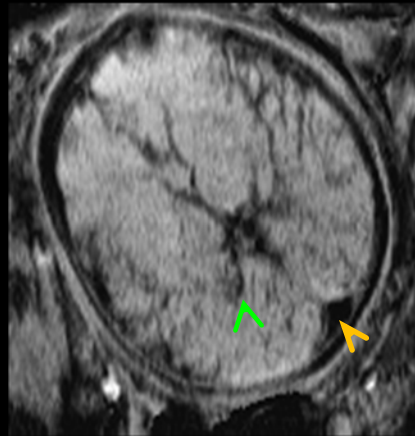
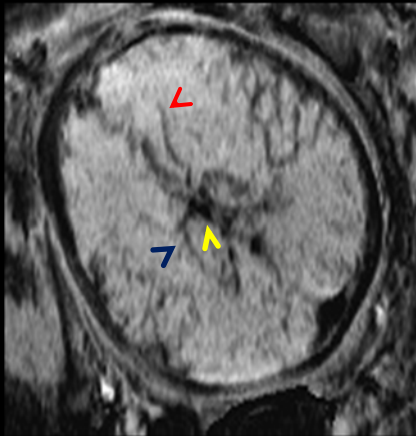
GA– 29 weeks

Radial Sampling
(0.52x0.52x2.00mm³)



All the sequence timing parameters between the radial and Cartesian MRA sequence are the same except for the effective voxel size.

SUSCEPTIBILITY WEIGHTED IMAGING



Septal vein

Thalamostriate vein

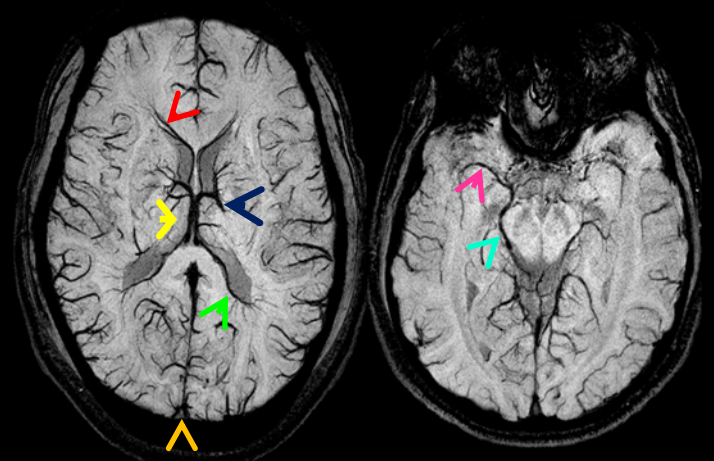
Internal Cerebral veins

Medial Atrial vein

deep Middle Cerebral Vein

Superior Sagittal Sinus

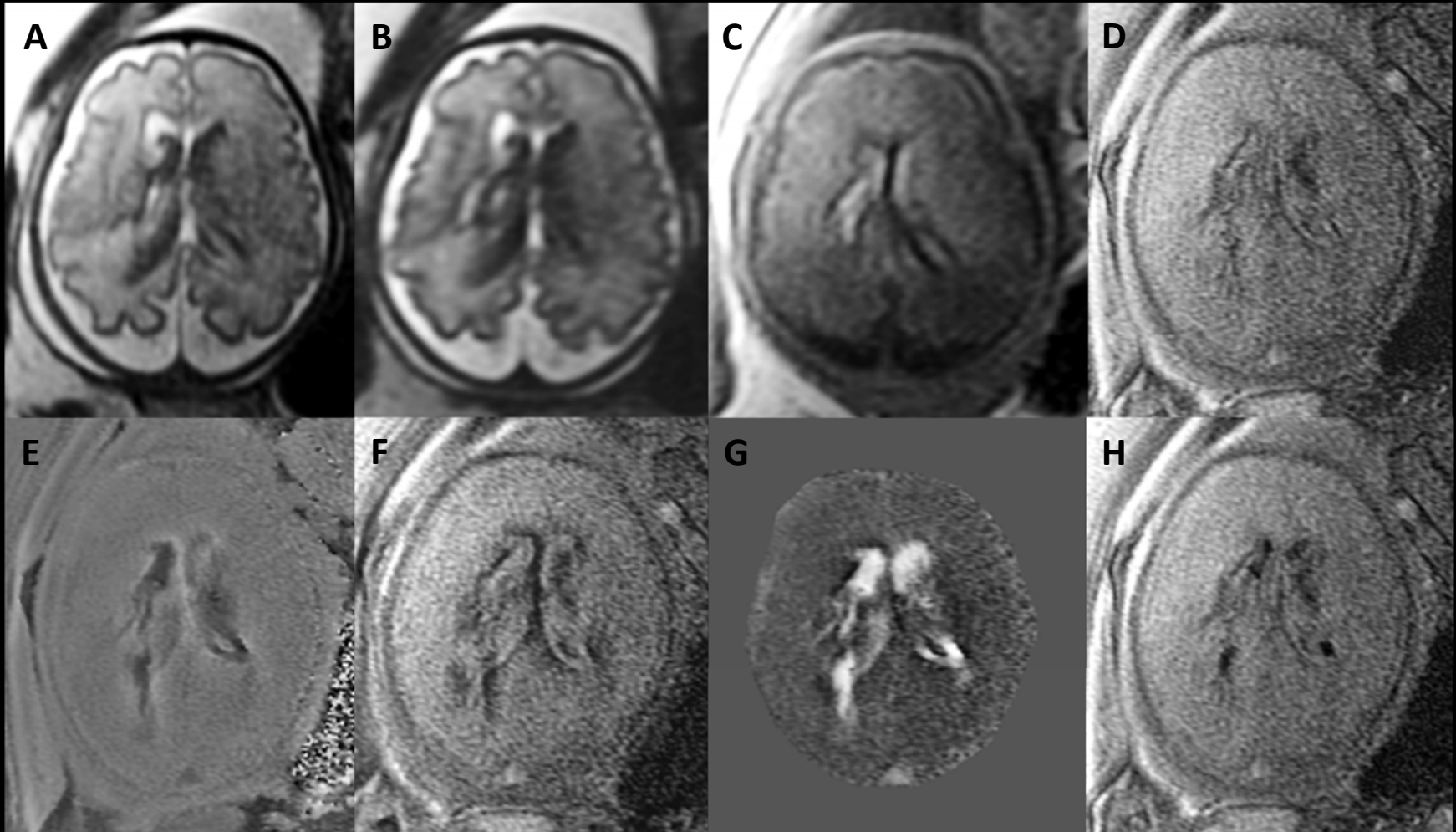
Basal vein of Rosenthal



Venogram in an adult subject

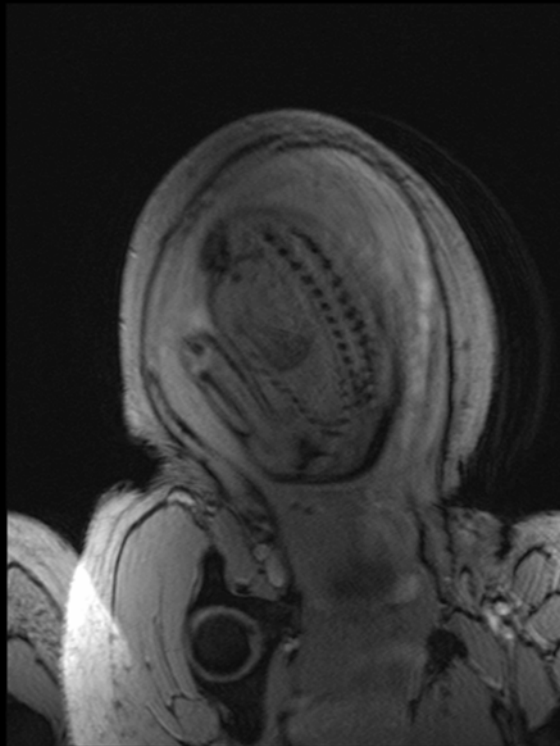
Neelavalli, J., Mody, S., Yeo, L., Jella, P. K., Korzeniewski, S. J., Saleem, S., ... & Romero, R. (2014). MR venography of the fetal brain using susceptibility weighted imaging. *Journal of Magnetic Resonance Imaging*, 40(4), 949-957.

DIAGNOSTIC ROLE OF SWI AND QSM IN DETECTING HEMORRHAGE



A- T2 Short TE; B – T2 long TE; C – T1 SPGR; D –SWI Magnitude (TE - 8.3ms); E – Processed SWI phase; F – Processed SWI ; G – QSM; H – Processed tSWI; Acquired on 1.5T
Note the hyperintensity in the ventricles on the QSM image (G) indicating extensive hemorrhage within the ventricles, which was not clearly identified in any other conventional sequences

FETAL BONE IMAGING WITH SWI

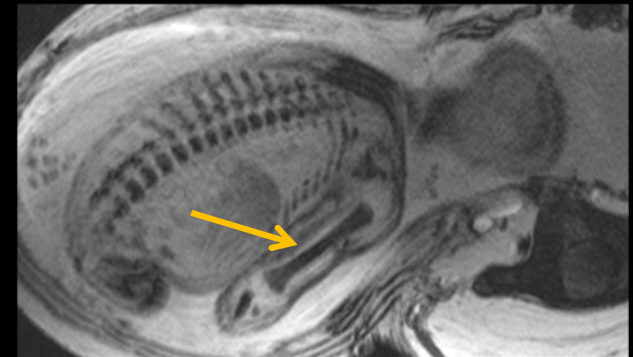


SWI Magnitude



SWI Phase

(~35 sec acquisition) 34 2/7 weeks

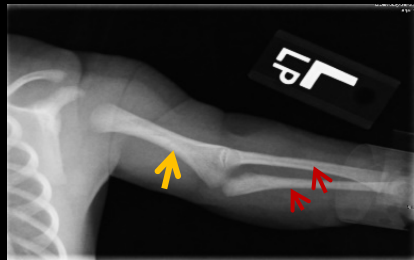


Humerus

CLINICAL APPLICATIONS OF SWI

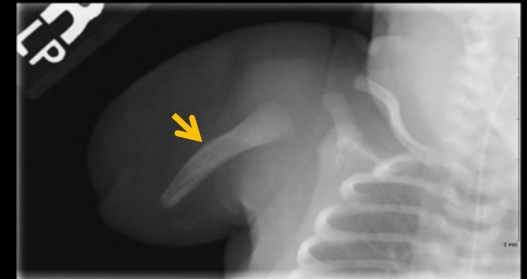
Fetal skeletal dysplasia

Post Birth X-ray

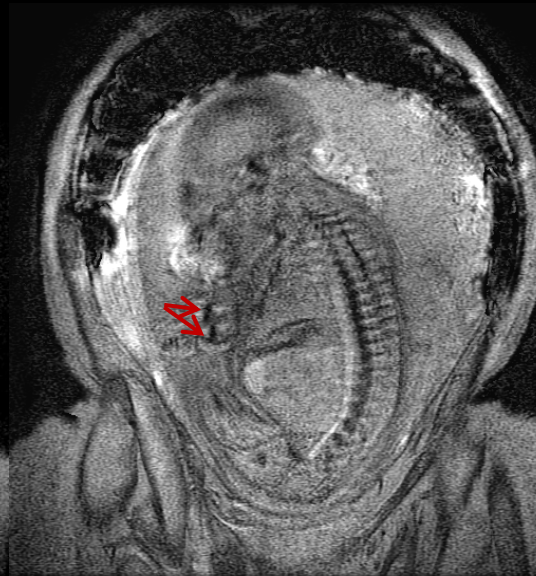


Left Humerus

Left Radius and Ulna

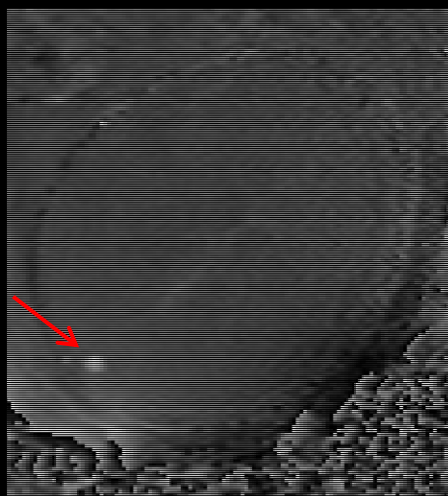


Right Humerus is short and
radius and Ulna are missing

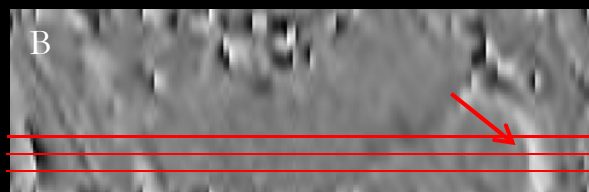
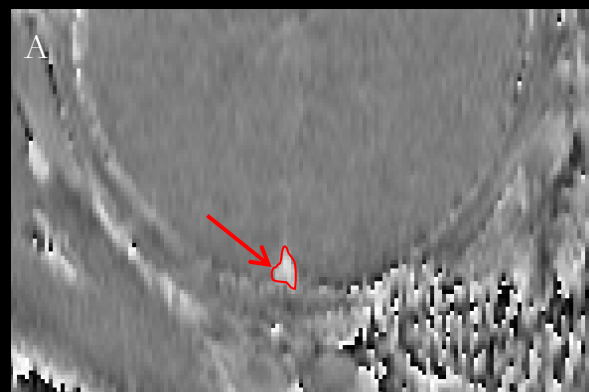


BLOOD OXIMETRY USING SWI

- Identify the SSS vessel lumen in two or more consecutive slices, and measure phase inside the vessel using a free hand ROI



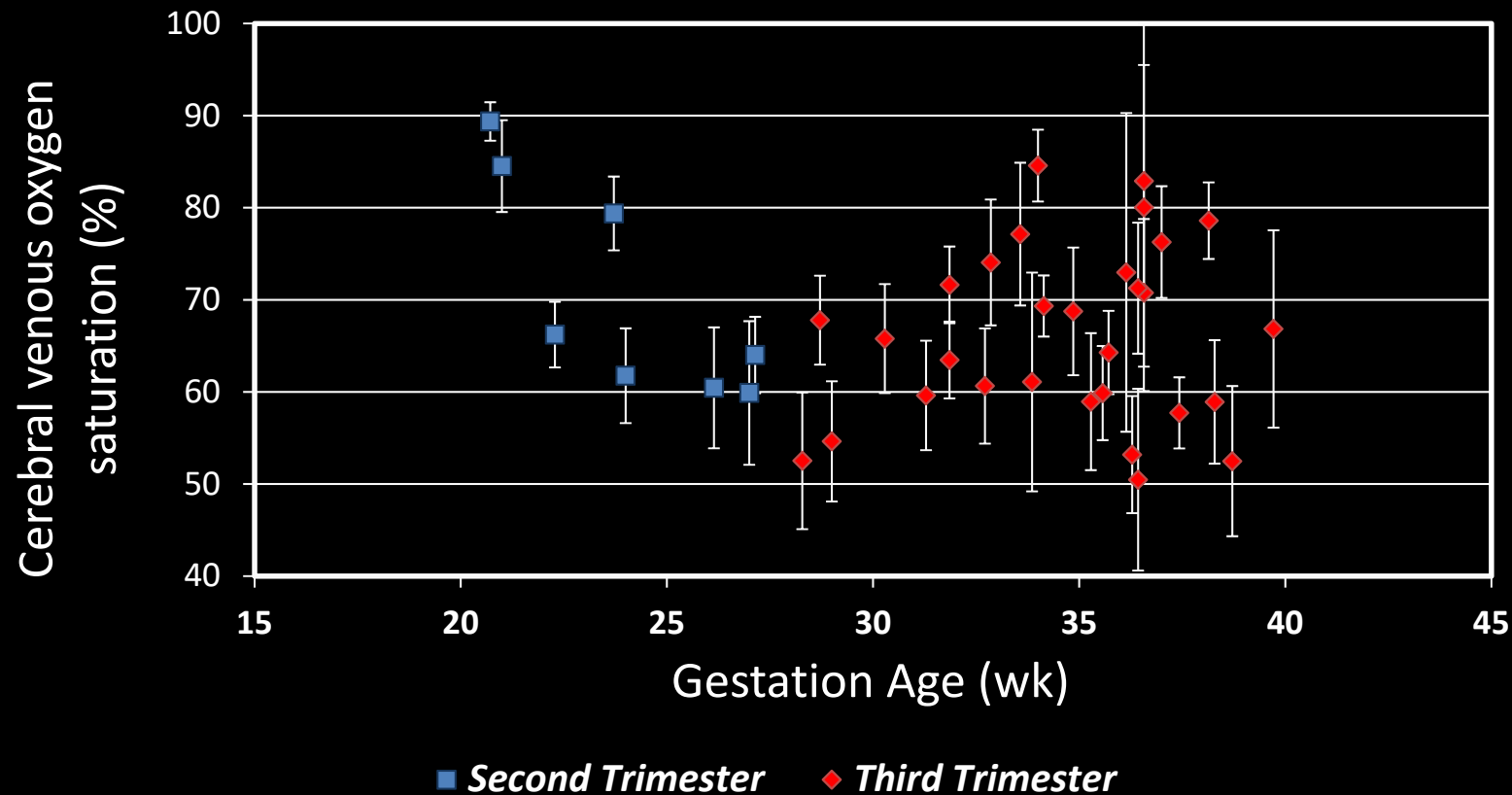
Phase Image



A vessel section which is relatively perpendicular to the slice direction is chosen with the help of sagittal view

FETAL BLOOD OXYGENATION: MR Susceptometry Results

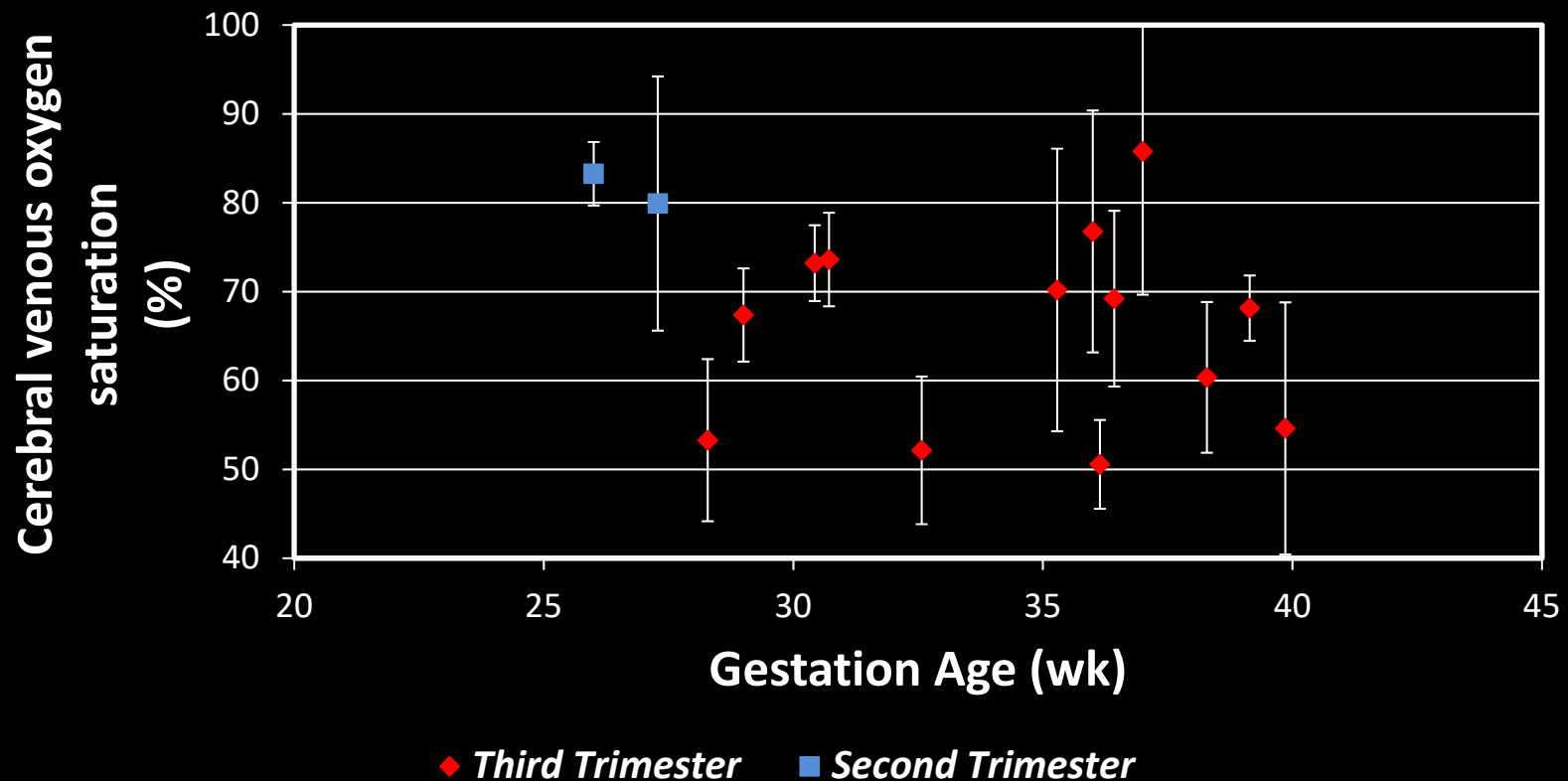
- Normal fetuses: Mean oxygenation = $66 \pm 9 \%$ (n= 40)



Blood oxygenation measured in the superior sagittal sinus of the fetus, using the infinite cylinder approximation. Measured 2D/3D Cartesian SWI.

FETAL BLOOD OXYGENATION: MR Susceptometry Results

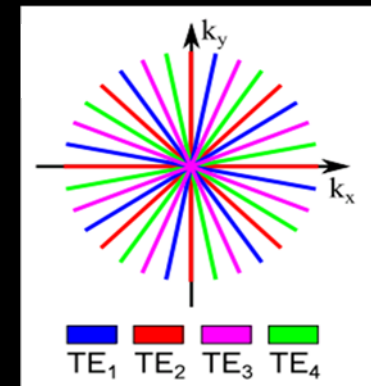
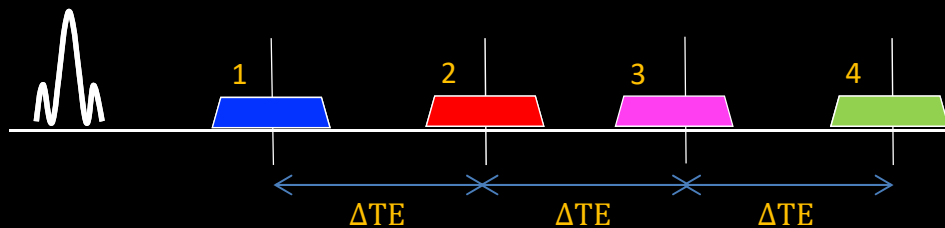
- IUGR fetuses: Mean oxygenation = $68 \pm 11\%$ (n = 15)



IUGR was defined based on estimated fetal weight being lower than 10th percentile

ACCELERATING SWI: SEGMENTED RADIAL ECHO PLANAR IMAGING

rSEPI - Acquiring multiple projections in single TR



Simulated Data

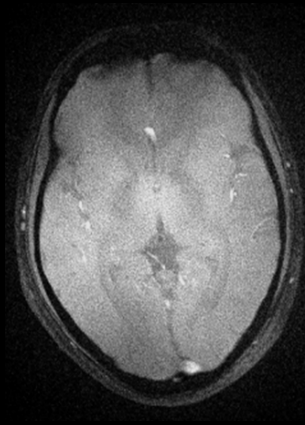
Original TE -11.5ms



Original TE -11.5ms

640 Spokes

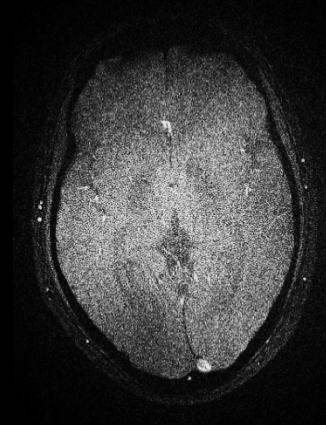
ETL 4/ ΔTE 3 in ms



ETL 4/ ΔTE 3 in ms

**640 Spokes
X 4 Acceleration**

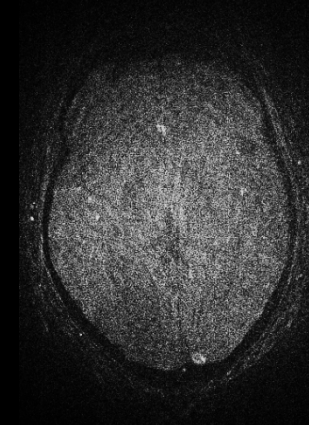
ETL 4/ ΔTE 3 in ms



ETL 4/ ΔTE 3 in ms

**320 Spokes
x 8 Acceleration**

ETL 4/ ΔTE 3 in ms



ETL 4/ ΔTE 3 in ms

**160 Spokes
X 16 Acceleration**

TR = 100ms, BW = 190hz/px, Voxel Size = 0.5x0.5x3mm³, FA = 20°, Multislice 2D radial.

CONCLUSIONS AND FUTURE DIRECTIONS

MRI fetal imaging has significantly matured.

New technologies allow structural, functional and metabolic studies in the fetus (and newborn).

Rapid image methods are likely to overcome motion problems in the near future.

Better gradients and rf coils may open the door to higher resolution and higher SNR to allow for imaging the fetus at younger and younger ages.

