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MRC Clinical Sciences Centre

Towards a comprehensive 3D MR imaging exam of the fetal brain *in utero*

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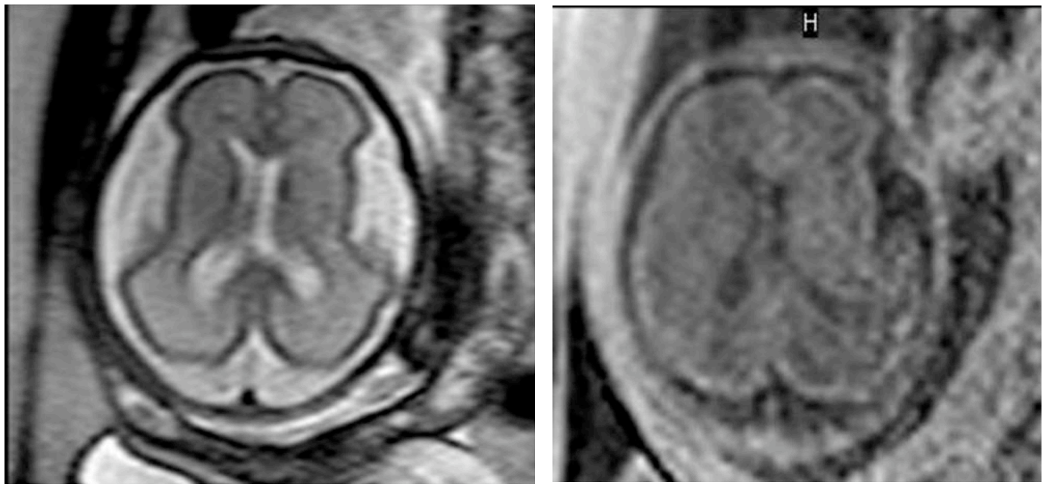
Standard ex-utero MRI Brain examination

- T1W (volume)
- PD/T2 multi-slice or T2W volume FSE
- FLAIR
- [Angiography]
- [DTI, fMRI, perfusion]

Fetal brain examination

- T2W ssFSE
- [T1W FFE]



27w Fetus

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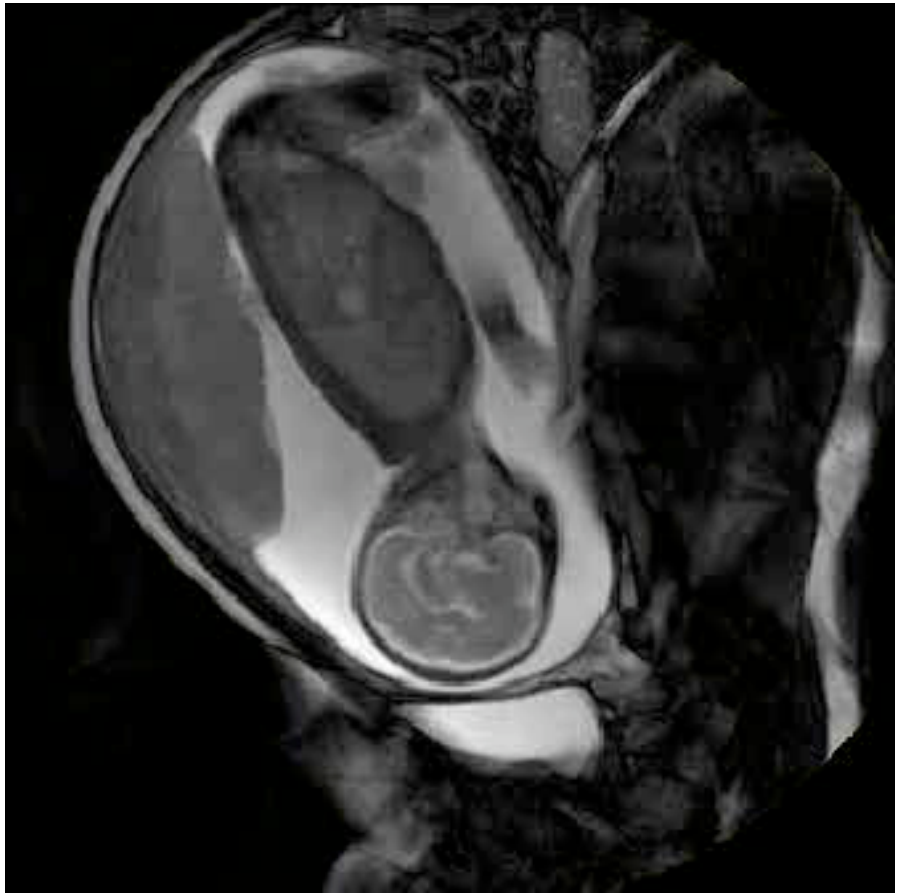
The challenge of the fetus



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Slice to Volume Reconstruction (SVR)

•Regard moving brain as a rigid body

•Use dynamic single shot MR scanning

•Work in image domain and exclude maternal tissue

•Make fetal images self consistent by image registration

•After position correction reconstruct a self consistent volume

Rousseau F. et al., Academic Radiology, 2006, 13 pp 1072-1081

Jiang S. et al., IEEE Trans Med Imaging, 2007, 26 pp 967-980

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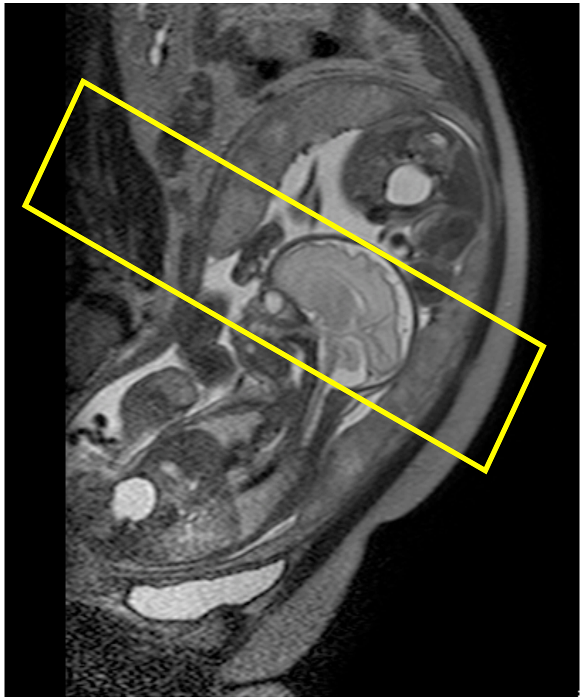
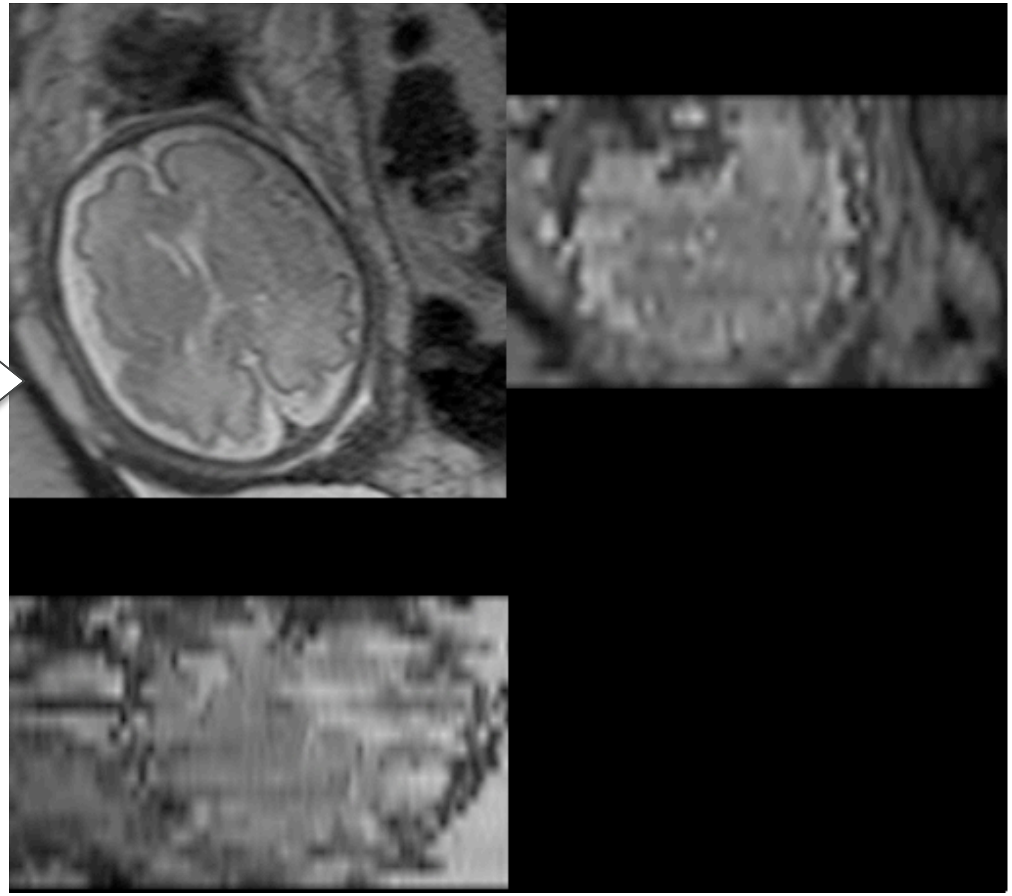
Motion damages the 3D view

Planned Scan Orientation



Fetus Moves



High in-plane resolution
other views are damaged

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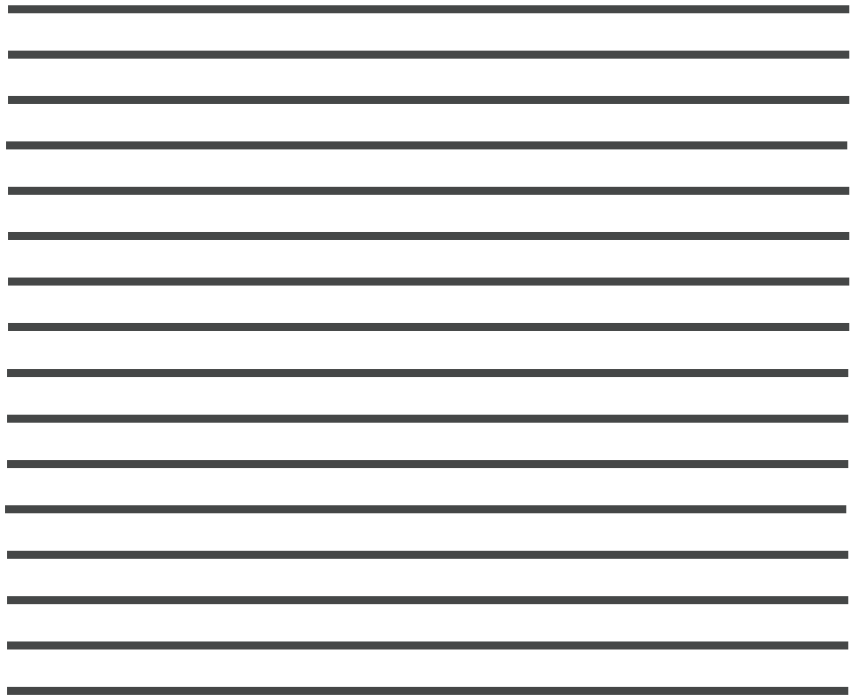
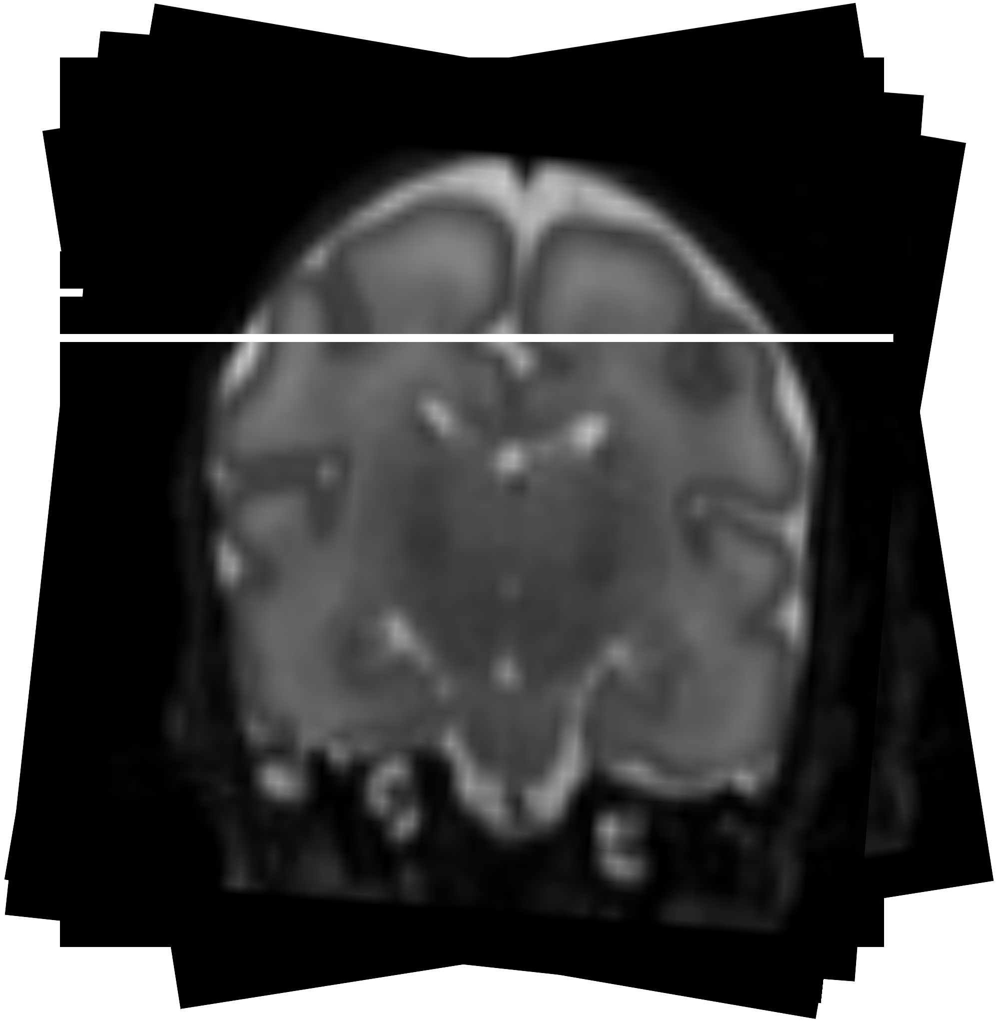
Slices prescribed in scanner co-ords



Slices prescribed in scanner co-ords



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Transform to fetal brain coordinate system

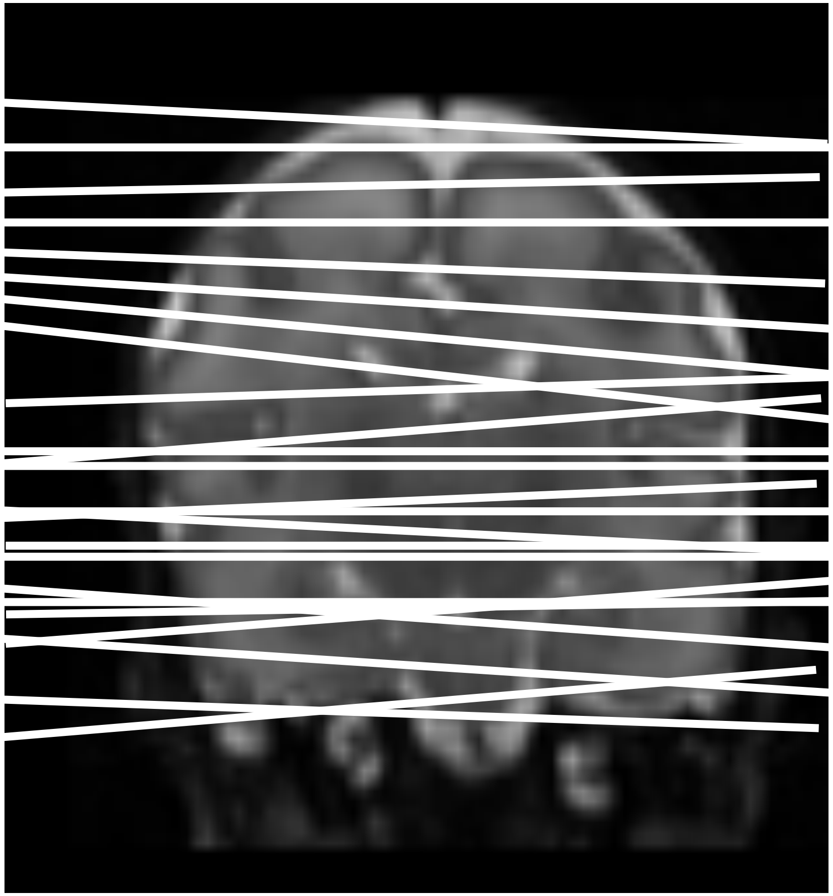
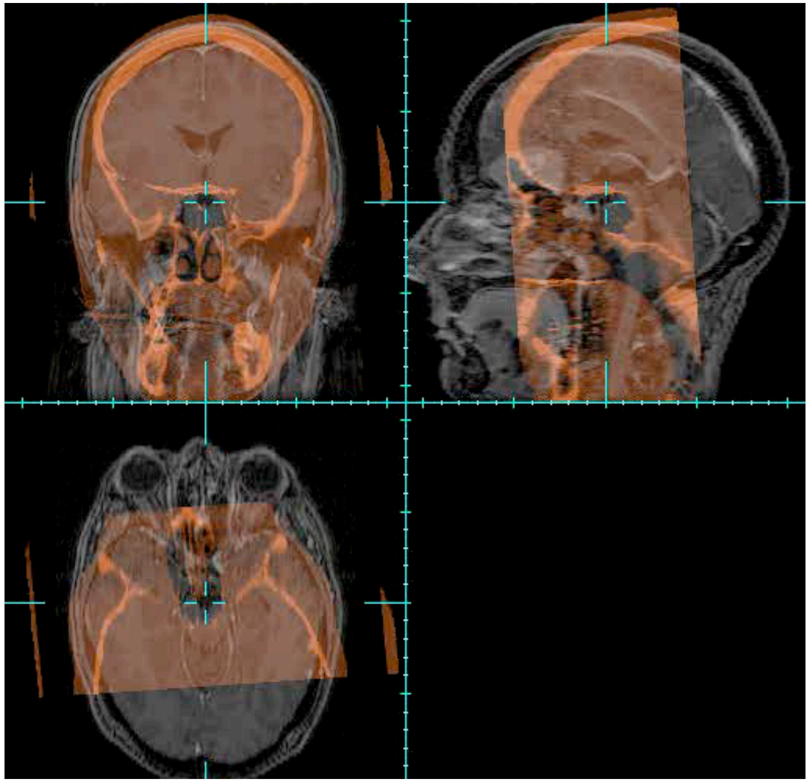


Image Registration

Image registration is the process of determining a mapping between the coordinates in one space and those in another, to achieve biological, anatomical or functional correspondence.



Rigid body registration of CT to MRI

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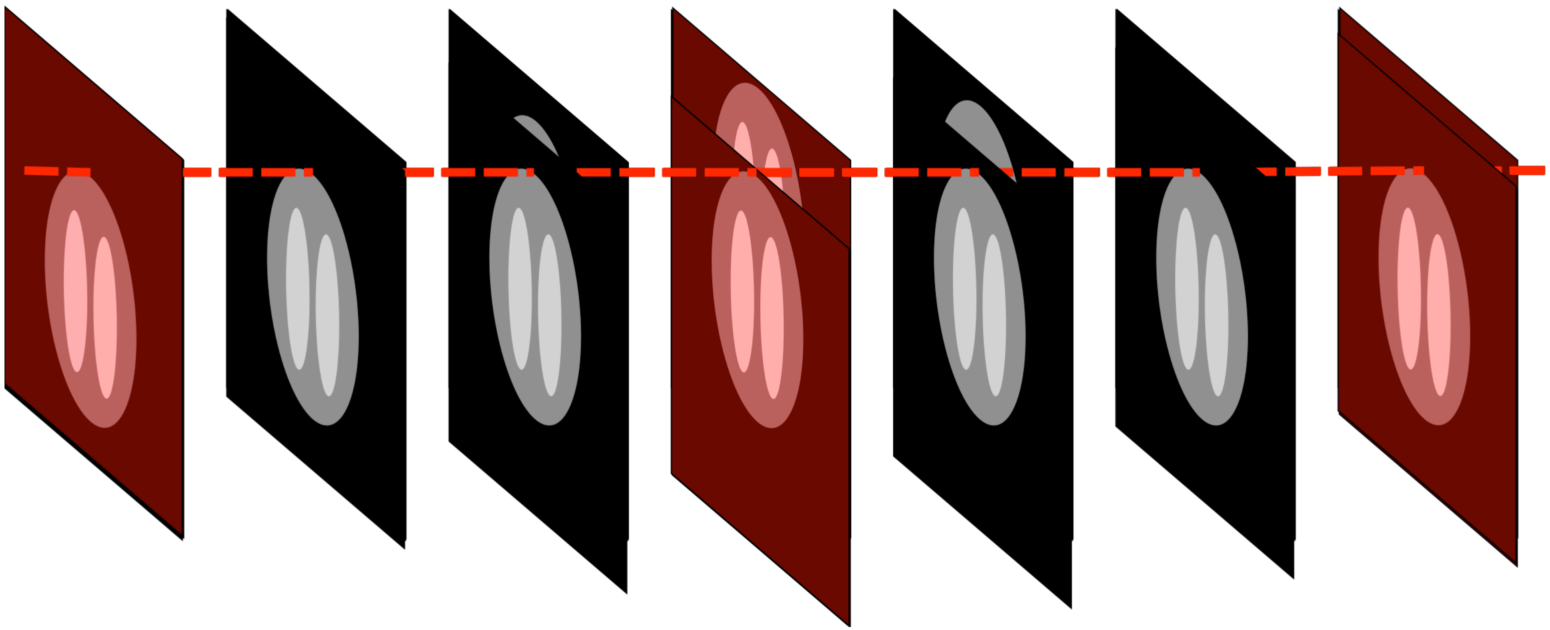
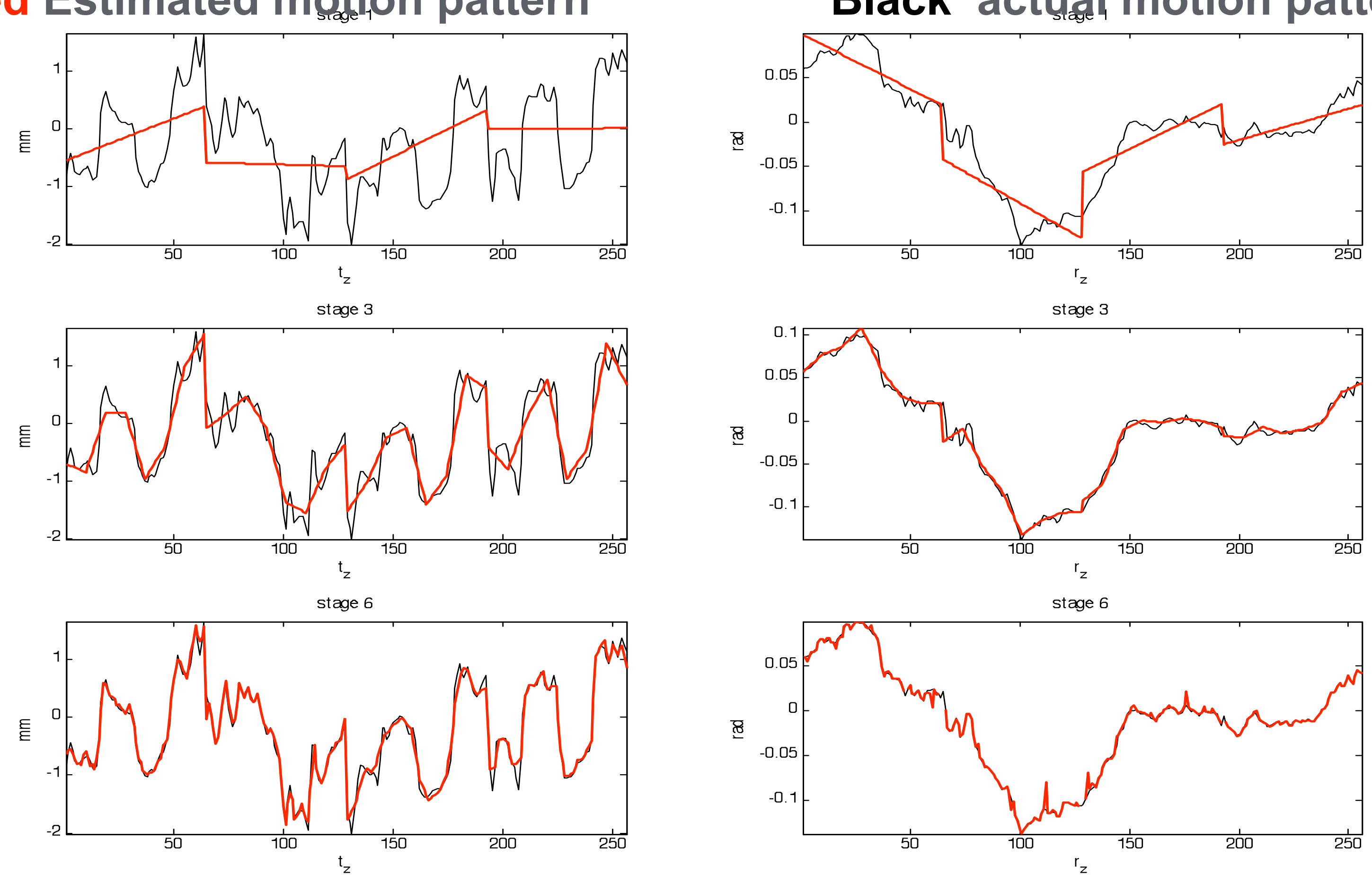
Chained slices

- 2D to 3D registration problematic
  - Very limited information from any single 2D slice
  - Lots of local optima of the cost function
- Use higherarchical registration to progressively refine motion estimate
- *Control slices* (shaded in red) are defined in each stage, which are free to move and affect the position of all their neighbours.



Example of an evaluation with synthetic data

Red Estimated motion pattern **Black** actual motion pattern



Accuracy 0.11 ± 0.2 mm for translations 0.24 ± 0.48 deg for rotations

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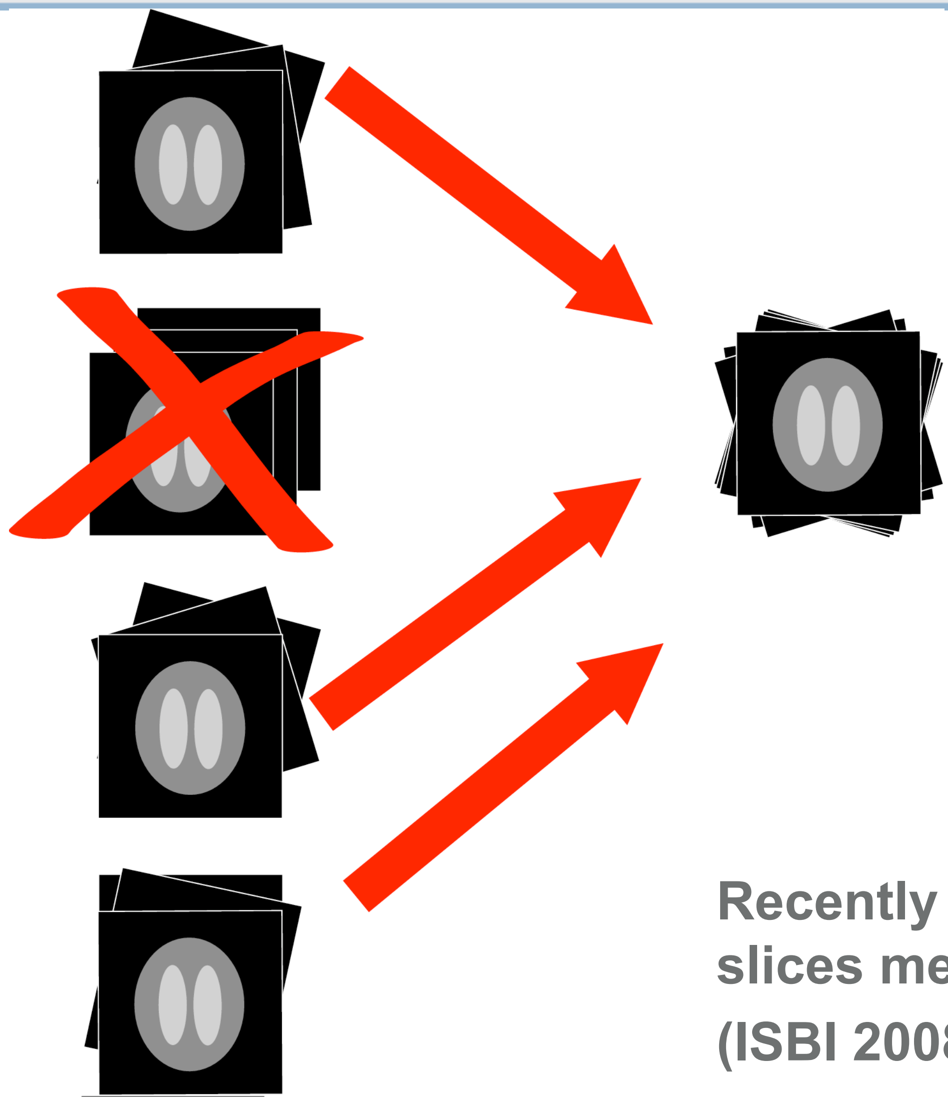
Estimating the target brain anatomy



- Registration to an anatomical target, which is unknown and must be estimated.
- Target made from all of the other images using the current estimated motion pattern

Recently a self-consistency of intersecting slices methods developed by Kim et al (ISBI 2008, p1167-1170)

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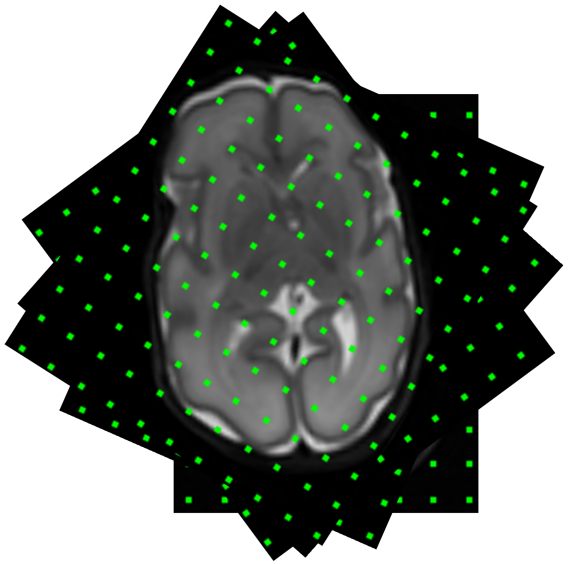
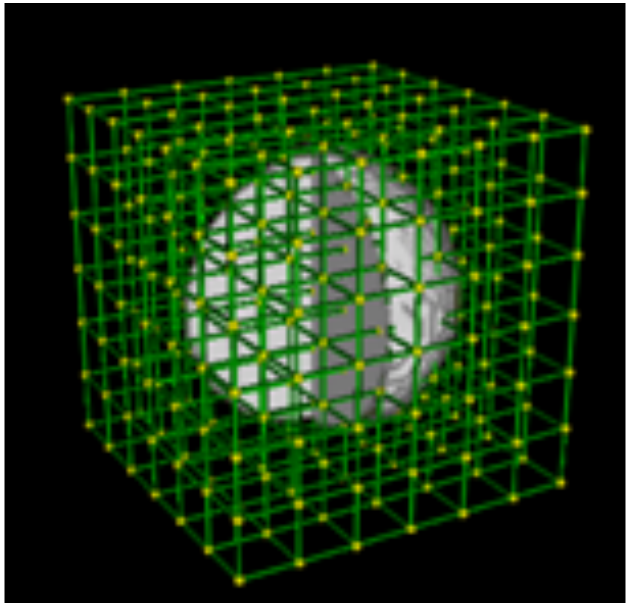
Reconstruction Method

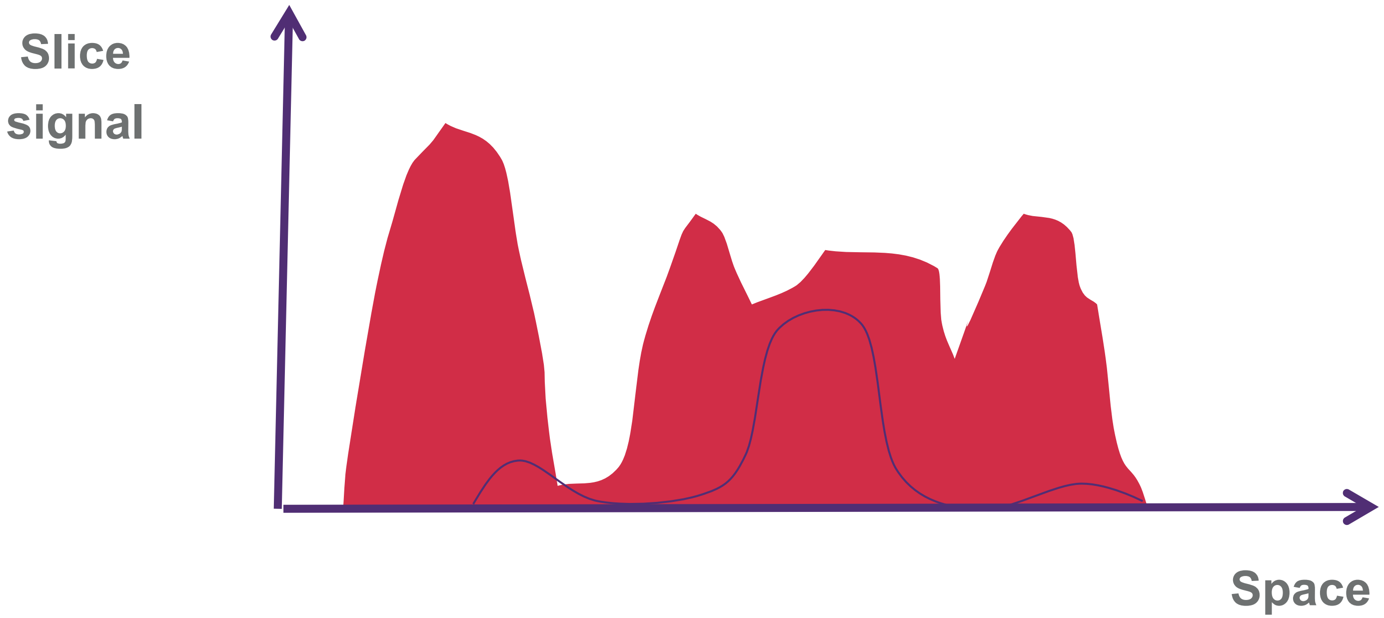
- Image data is irregularly spaced in the anatomical coordinate system
- Reconstruct onto a regular grid requires scattered data interpolation
- We use a B-Spline algorithm for scattered data [1].



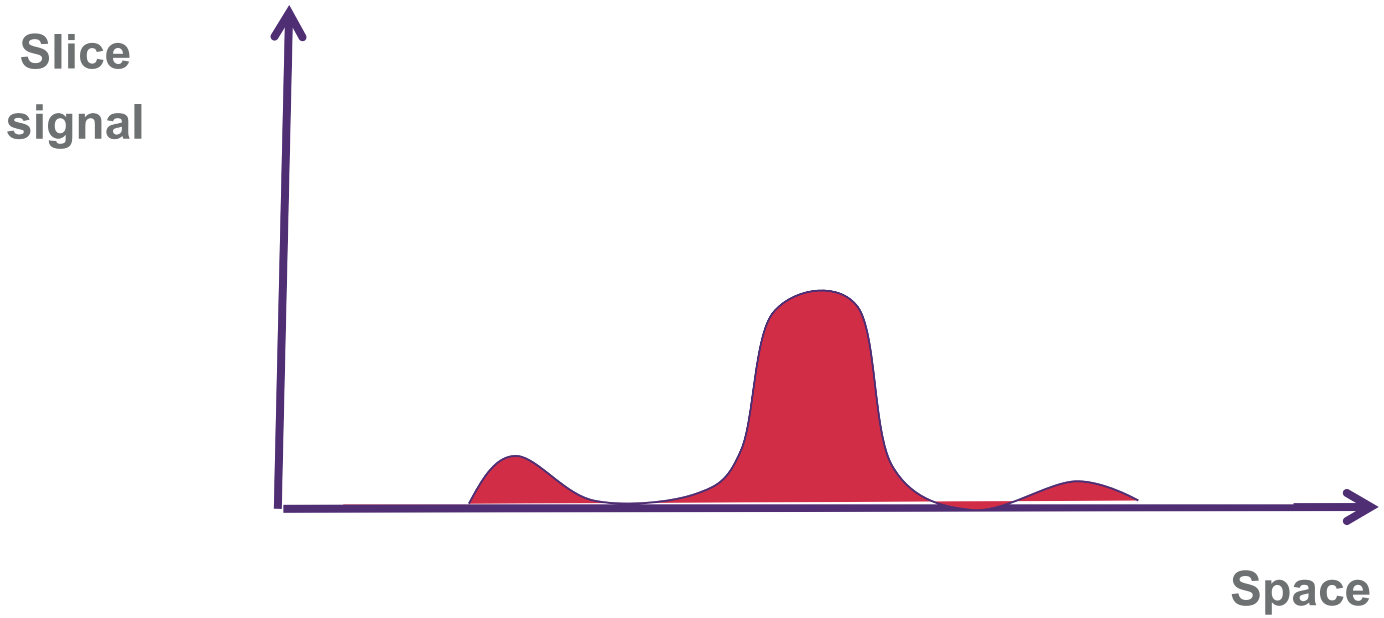


[1] Lee et al., IEEE Trans VCG 3, pp. 228-244, 1997

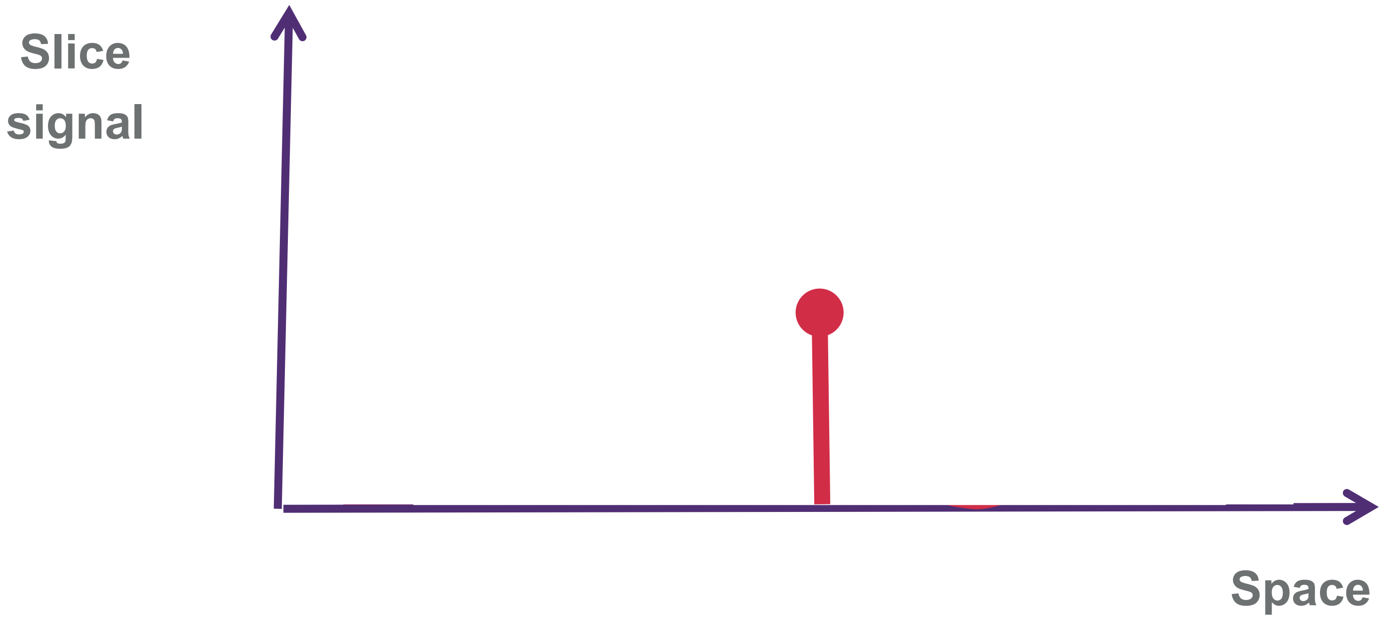
Slice selection



Slice selection



Slice selection



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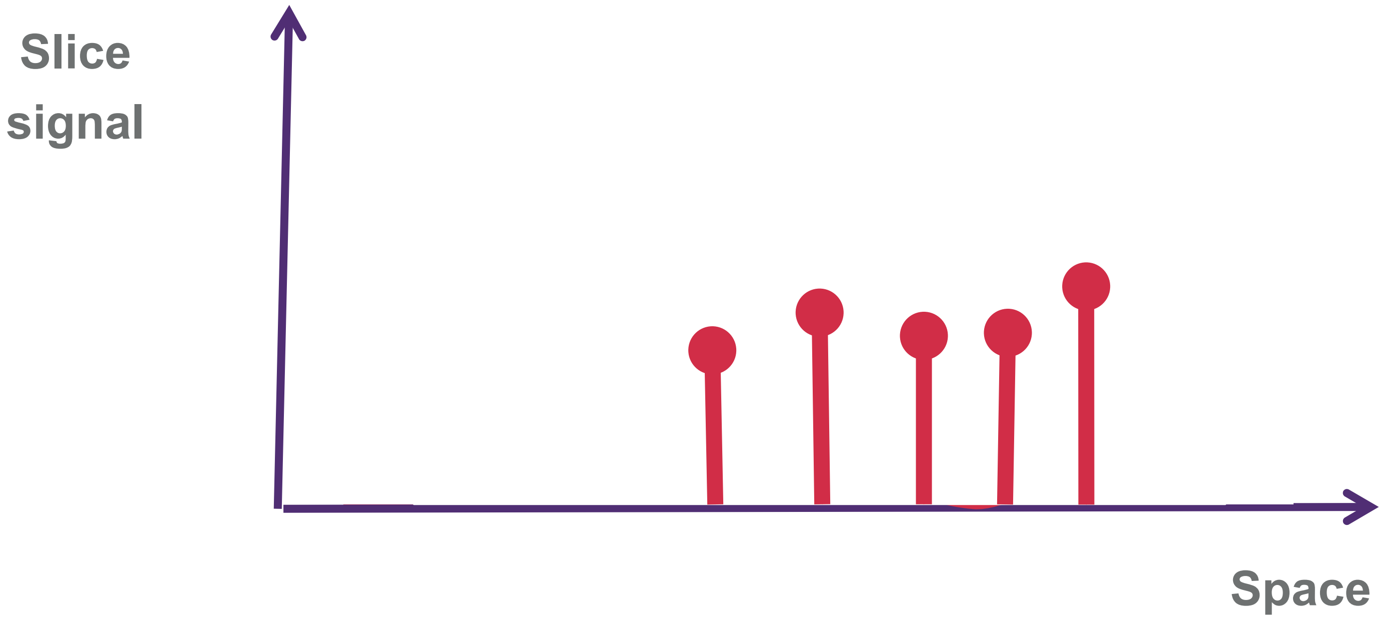
Slice selection



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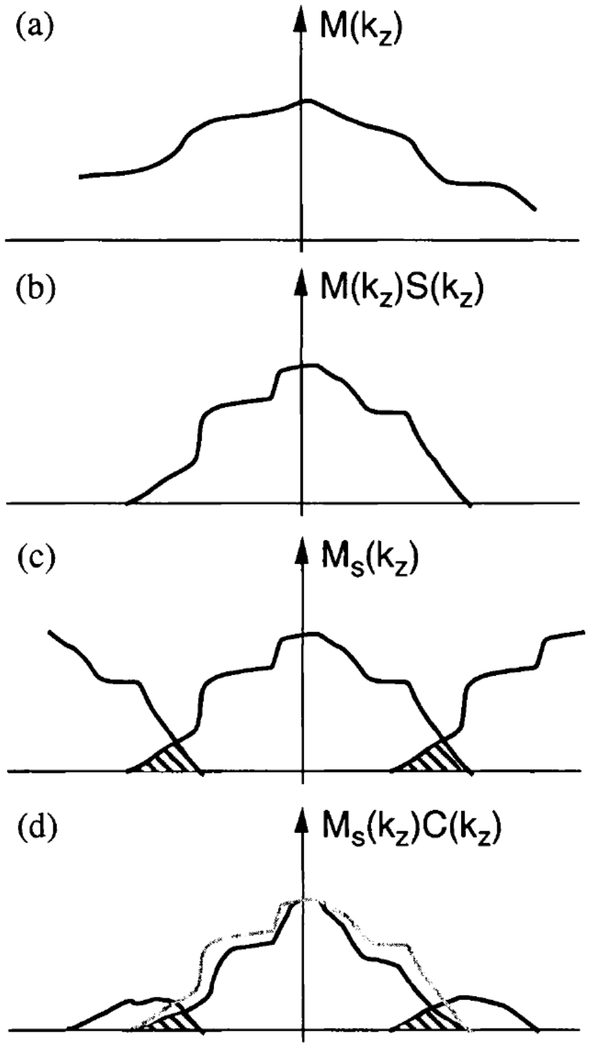
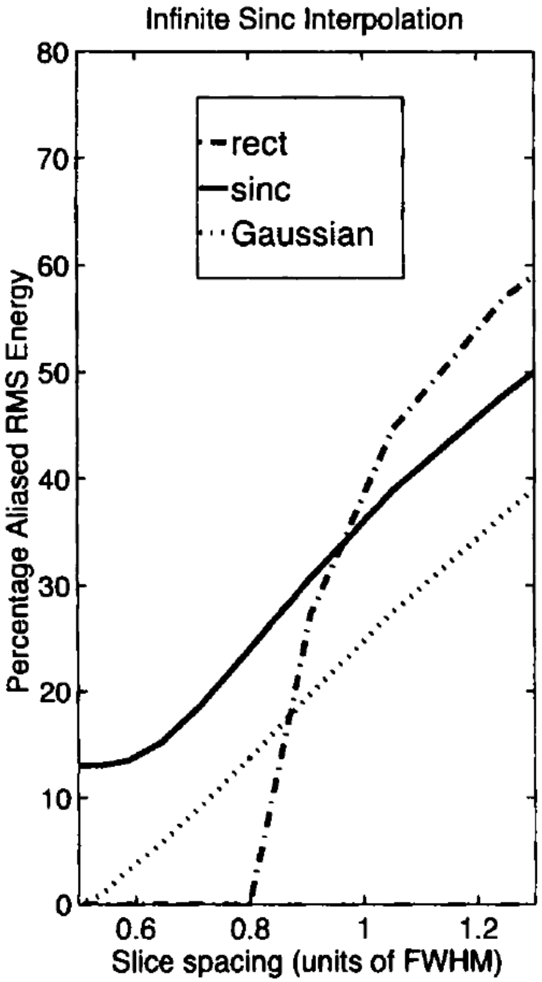
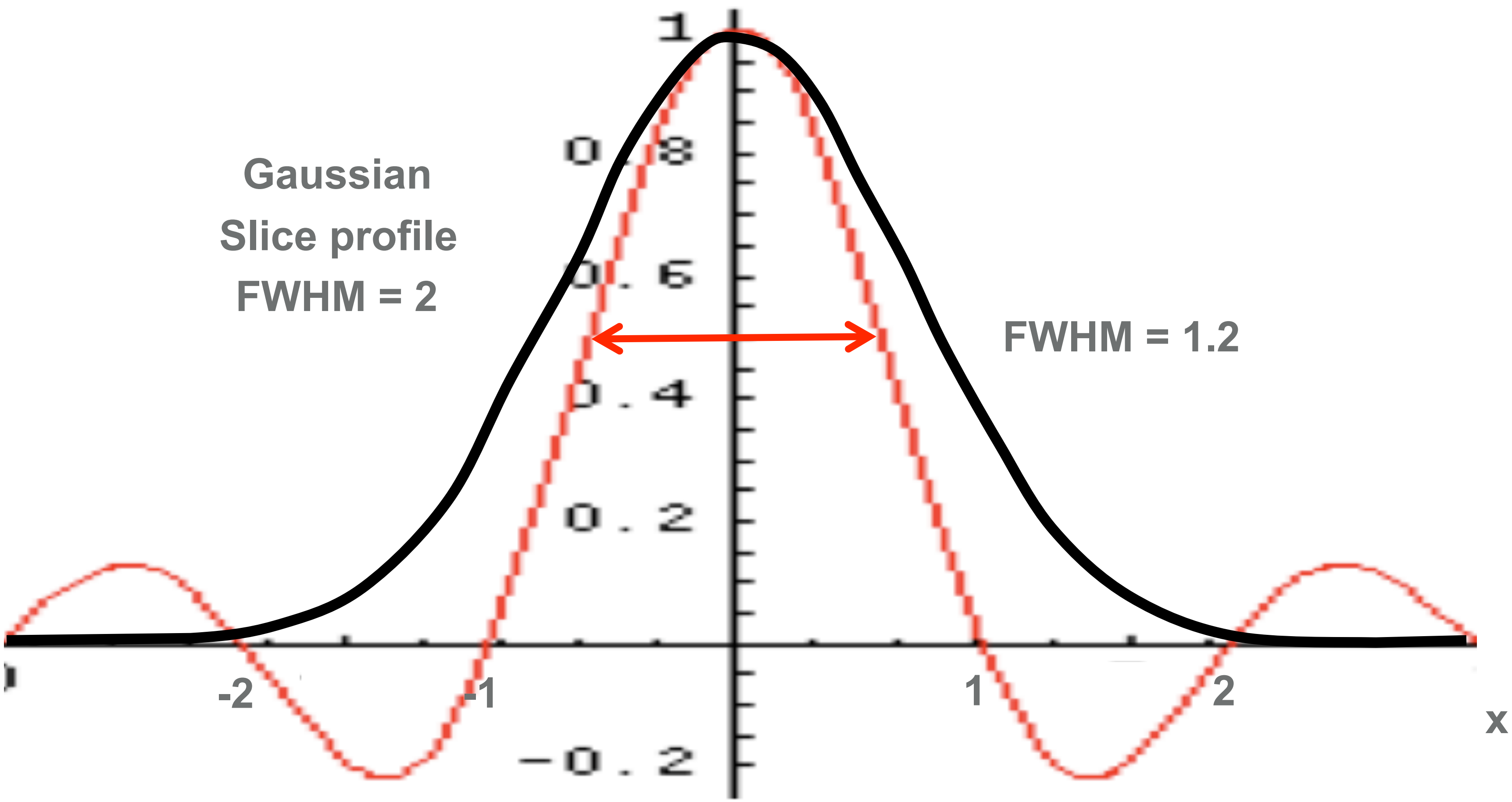
A frequency domain view of slice selection



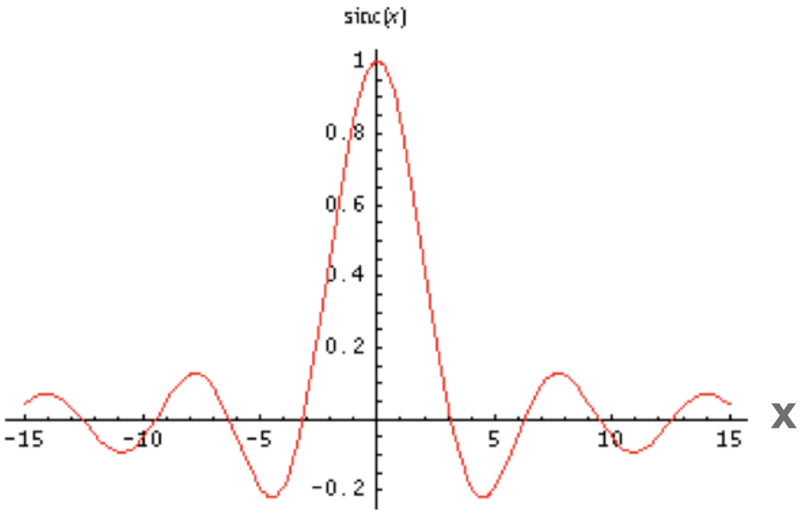


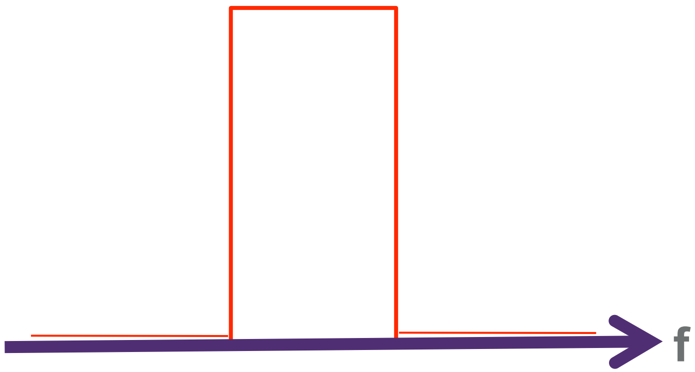
Noll et al MRM 1997

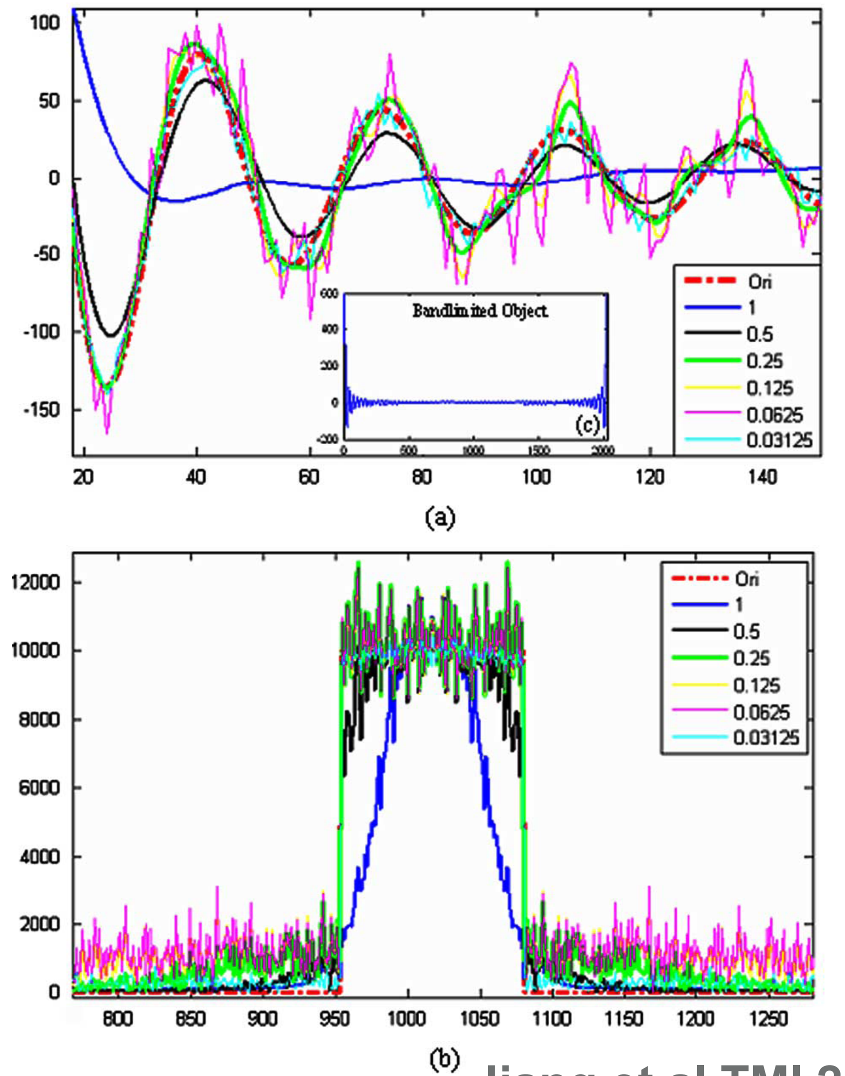
Choosing slice thickness



Reconstruction bw







Jiang et al TMI 2007

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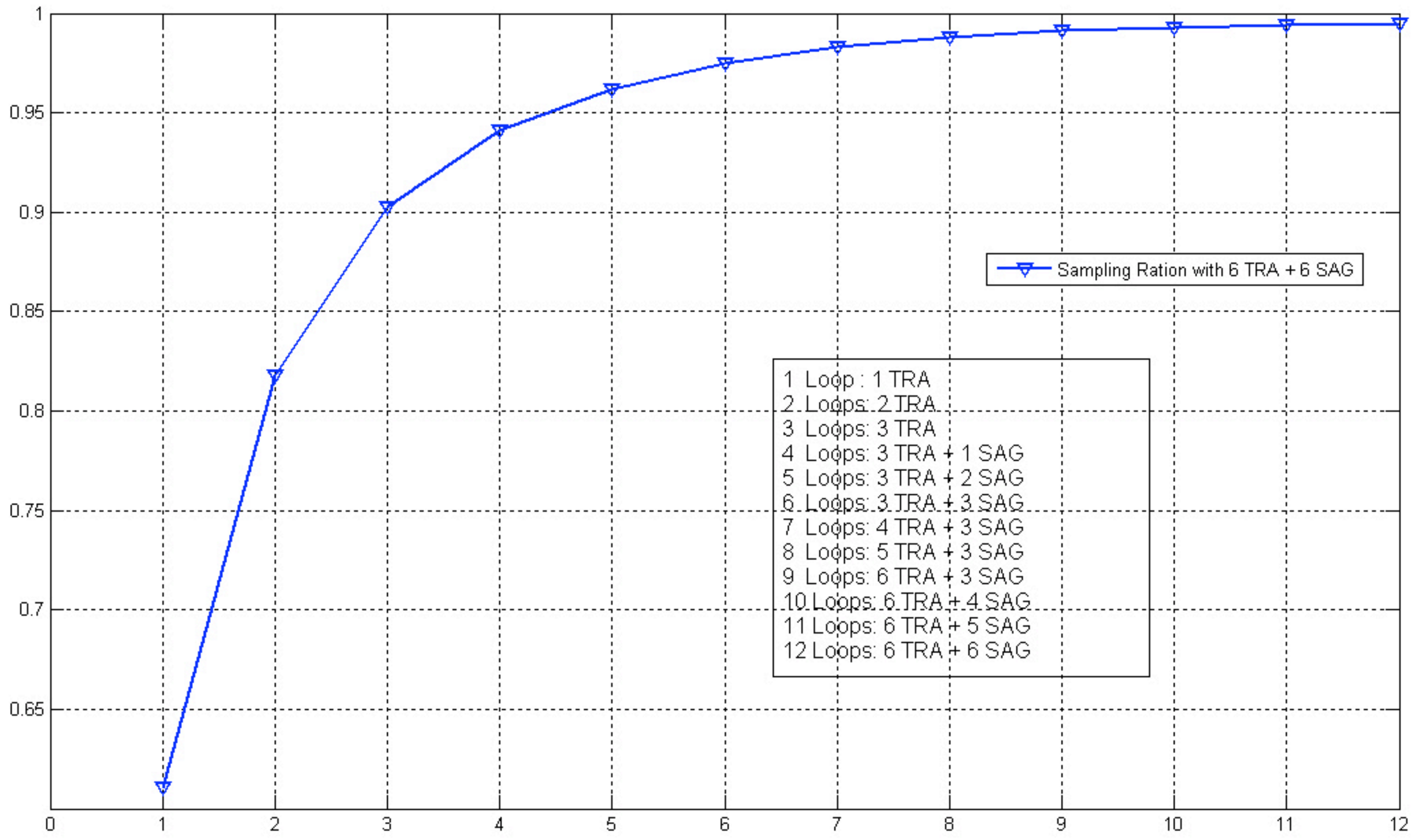
Fraction of pixels containing a data point



Pilot study

20 fetuses, with gestational ages ranging from 22 to 31 weeks, were scanned using a 1.5T Philips Achieva scanner, with this protocol

- Single shot fast spin echo sequence (ssFSE)
- T_R: 1046 ms, T_E: 120 ms
- Voxel size: 1.18 x 1.18 mm
- Slice thickness: 2.5 mm, slice gap: -1.25 mm
- Number of slices: 60
- No breath-holds or sedation of either mother or fetus was used
- 6 to 8 image sets acquired per child: 2-4 transverse, 2 coronal, 2 sagittal
- Total scanning time: 5 to 8 minutes

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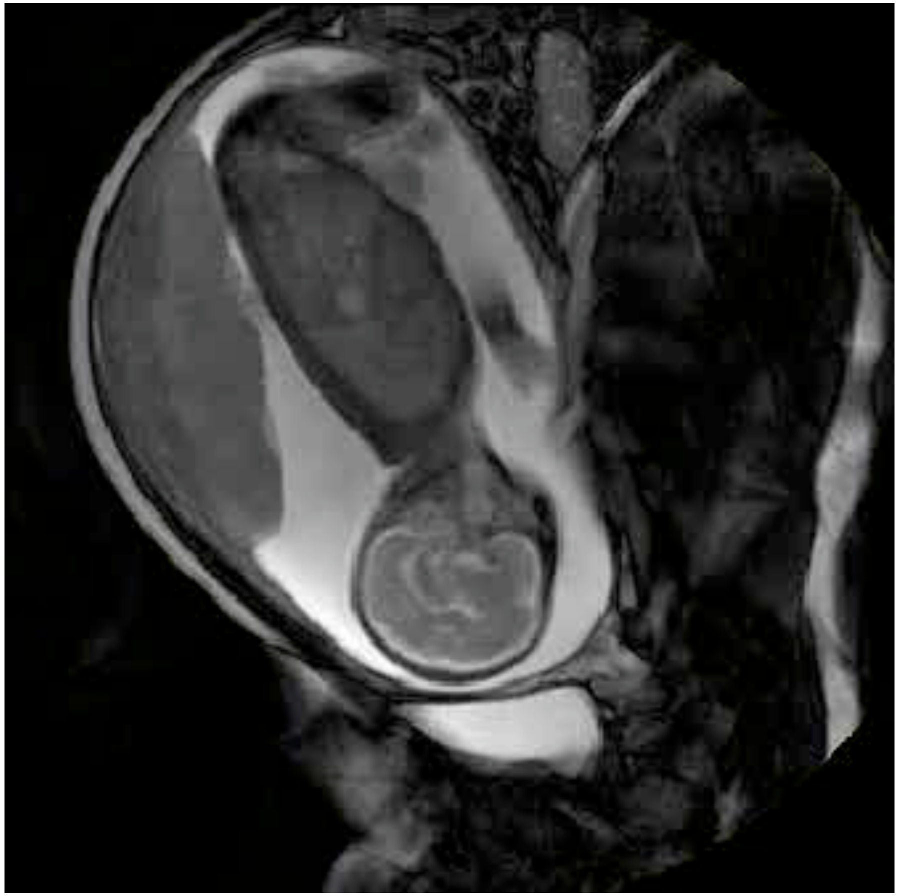
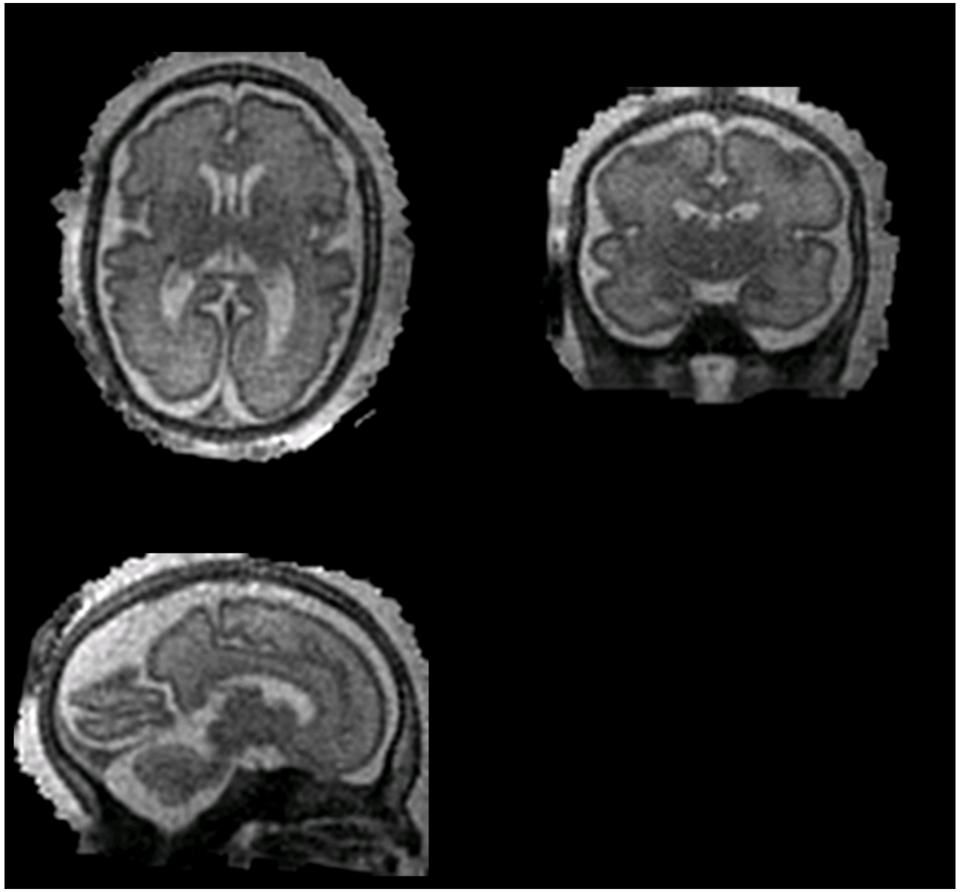
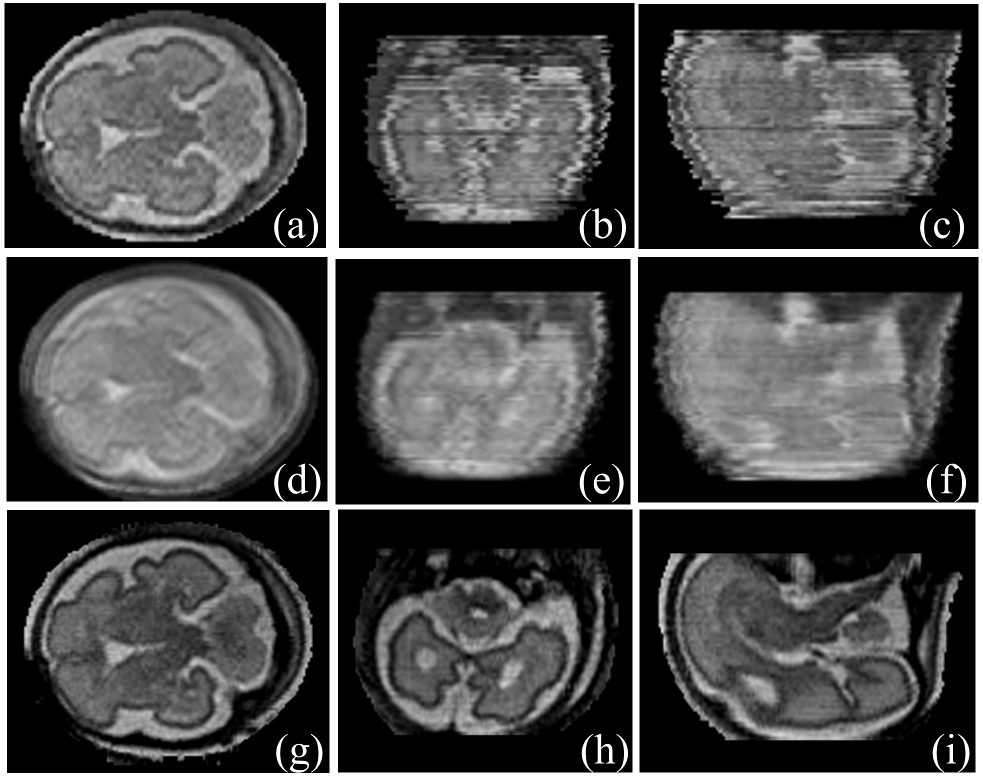
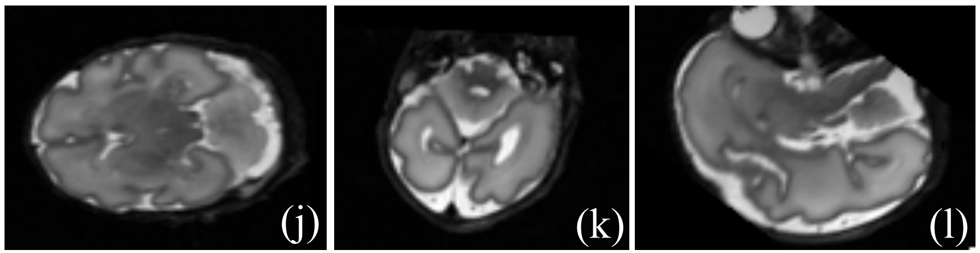
Reconstructed brain images





28 week Normal fetus





(a)-(c) are acquired fetal MR transverse data viewed in 3D planes with 1.08mm*1.45mm in-plane resolution and 2.5mm TH.

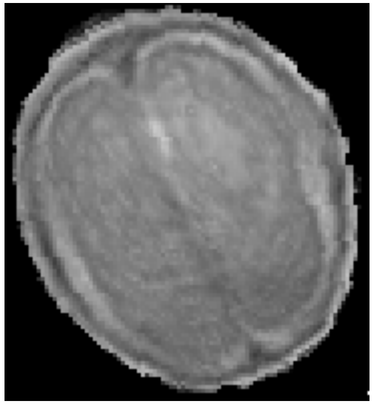
(d)- (f) are the corresponding views for averaged images from the full dynamic scan before motion correction.

(g)- (i) are the corresponding views reconstructed to 0.74mm isotropic resolution image after registering slices from 3 orthogonal orientation.

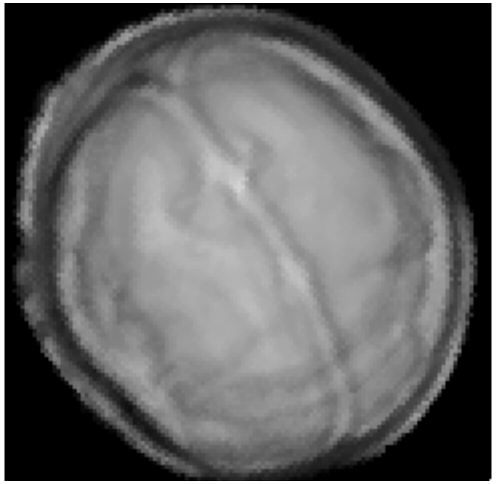
(j)- (l) are the corresponding views of a preterm neonate born at 28 week and scanned at 30 week with 0.98*0.98mm in-plane resolution and 1 mm TH at 3T.

Development of the cortex: GA 23 w to 35 w

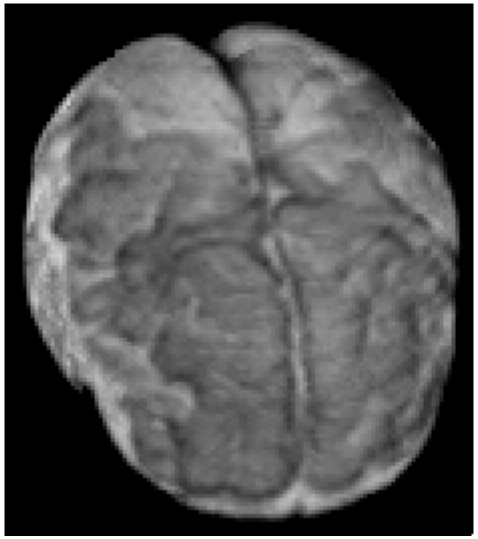
GA: 23 W



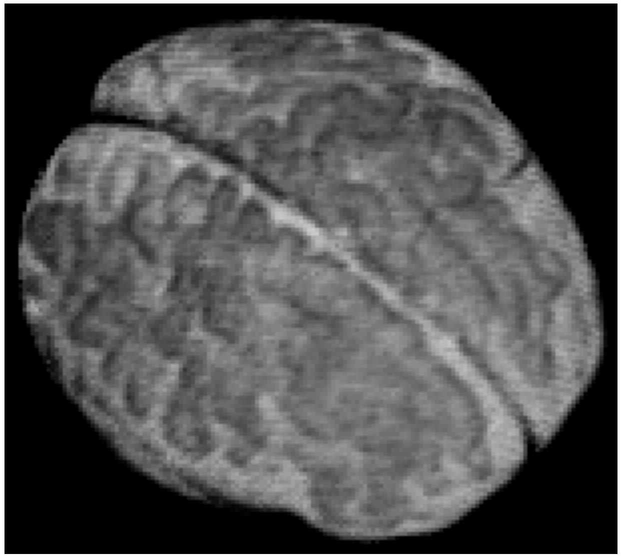
GA: 27 W



GA: 33 W



GA: 35 W



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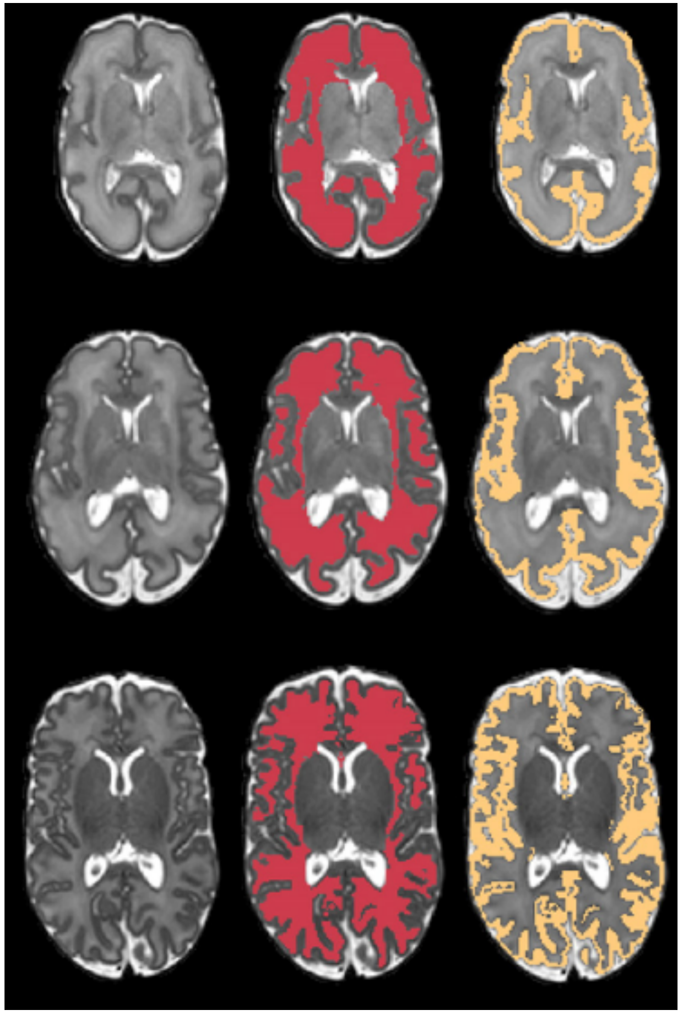
Cortex extraction

•A set of 10 reconstructed images were segmented using an algorithm designed for the neonatal brain [1].

•Segmentation in the developing brain is more challenging that in adults, as contrast changes considerably during maturation. Also, partial volume effects produce voxels incorrectly labelled as WM in the border between GM and CSF.

•The method corrects mislabeling due to partial-volume effects increasing its accuracy against conventional algorithms. Quantitative tests against manual segmentations show good performance.



Segmented WM (Red) and GM (orange)

[1] Xue H. et al., Neuroimage 38, pp 461-477

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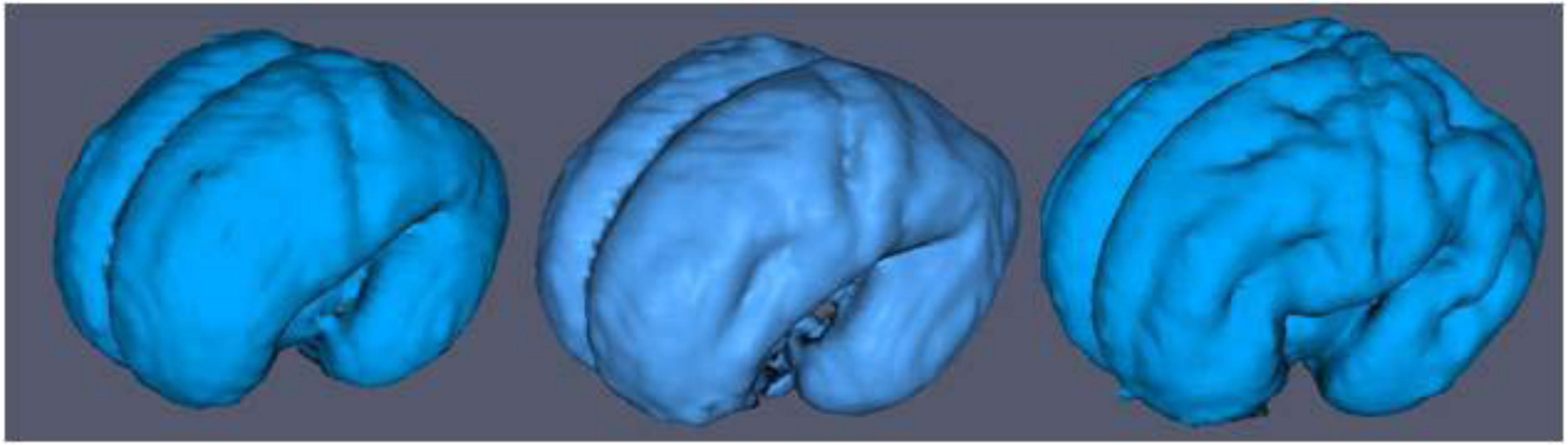
Surface reconstructions of 3 cortices



24 weeks **27 weeks** **30 weeks**

Reconstructed surfaces of the white matter-cortex boundary were produced using a level sets methods as described by Xue H. et al. (Neuroimage 38, pp 461-477)

Bertelsen 2009, Aljabar

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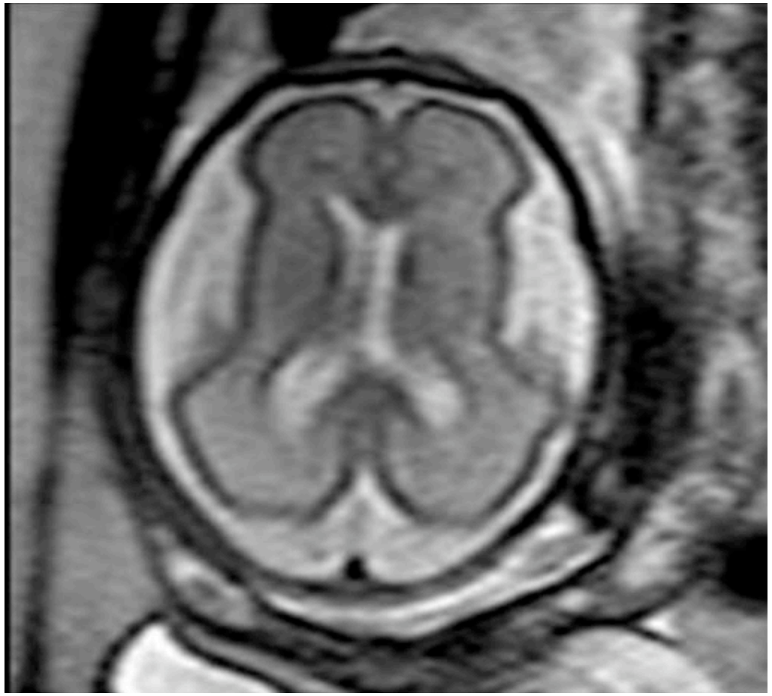
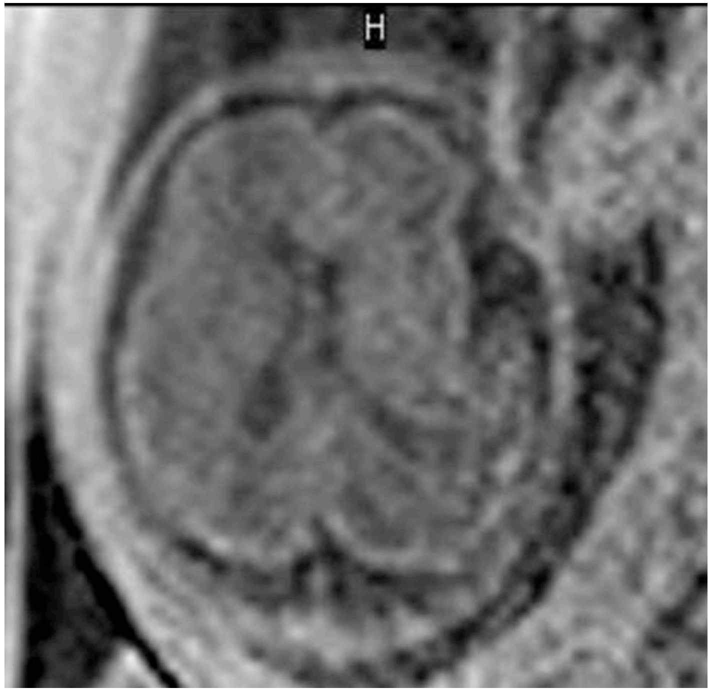
T1 weighted imaging



T2w ssFSE



T1w FFE

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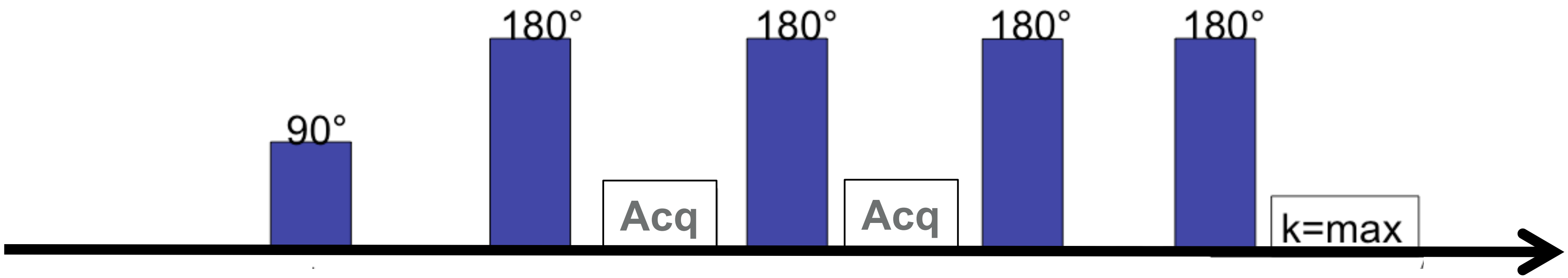
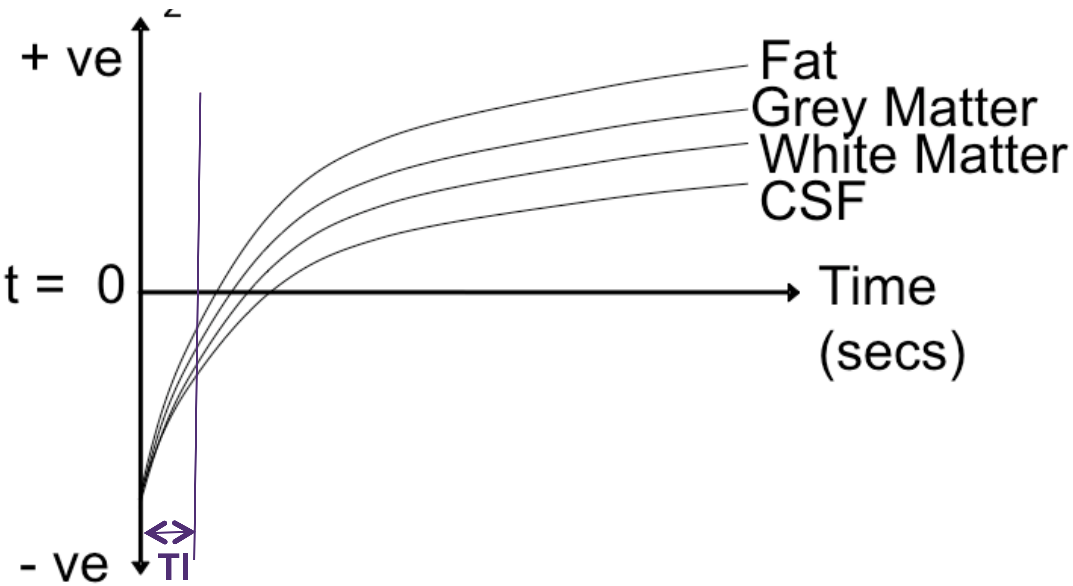
From T2w ssFSE to T1w ssFSE





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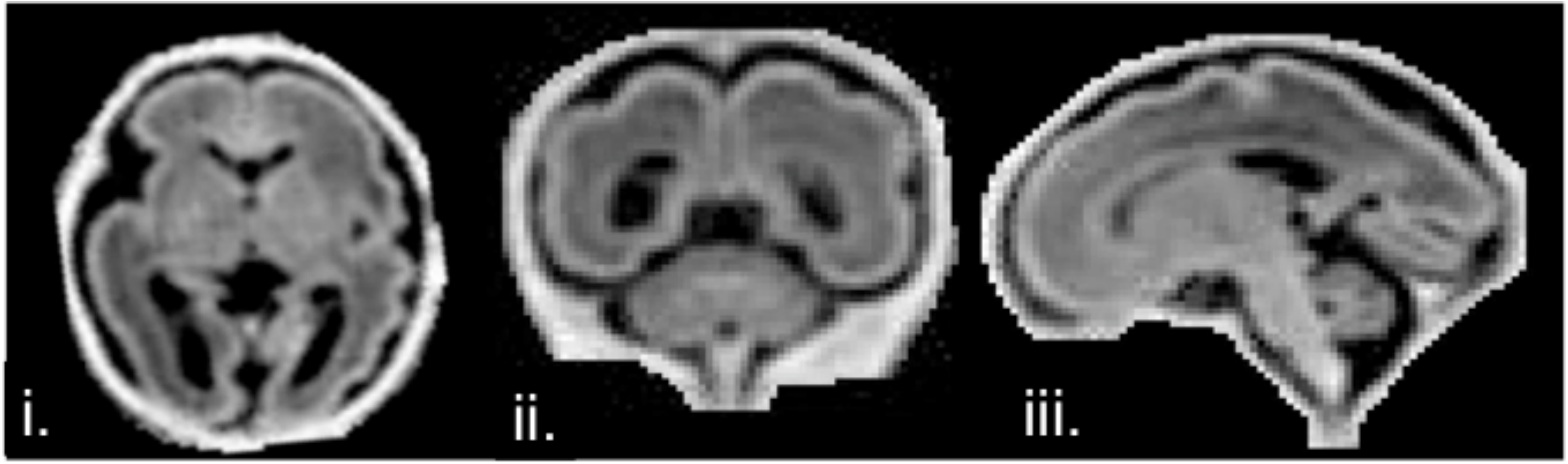
SNAPIR (TI = 400)



SNAPIR - SVR

In-utero DWI/DTI remains very challenging

Requires multiple shots of consistent data for each slice

- DTI needs at least 7 non-linear directions of diffusion weighting
-

Estimates of ADC have been obtained in 20 sec breahold

- Baldoli et al 2002, Righini 2002

Full DTI generally requires longer scans

- Bui et al 2006: 53 second acquisition, sedation.
- Kim et al 2008: 18 sec acquisition, breathold
- Kasprian et al 2008: 1m49sec
  - » Fetus in the 'favorable "immobilized" head position in the lesser pelvis'
  - » Extracted tracts

Extending SVR to DTI

Contrast different in b_0 and each differently sensitized image

- Use more general registration cost function [1]
- Move to model based registration approach [2]

As realign slices into anatomical space, must take care of sensitization directions [1]

$$I = I_0 * \exp(-bg' D_{Lab} g) = I_0 * \exp(-bg'(R' D_{Ana} R) g)$$

1. Jiang et al 2009, MRM; Bertelsen et al, 2009, ISMRM p6416

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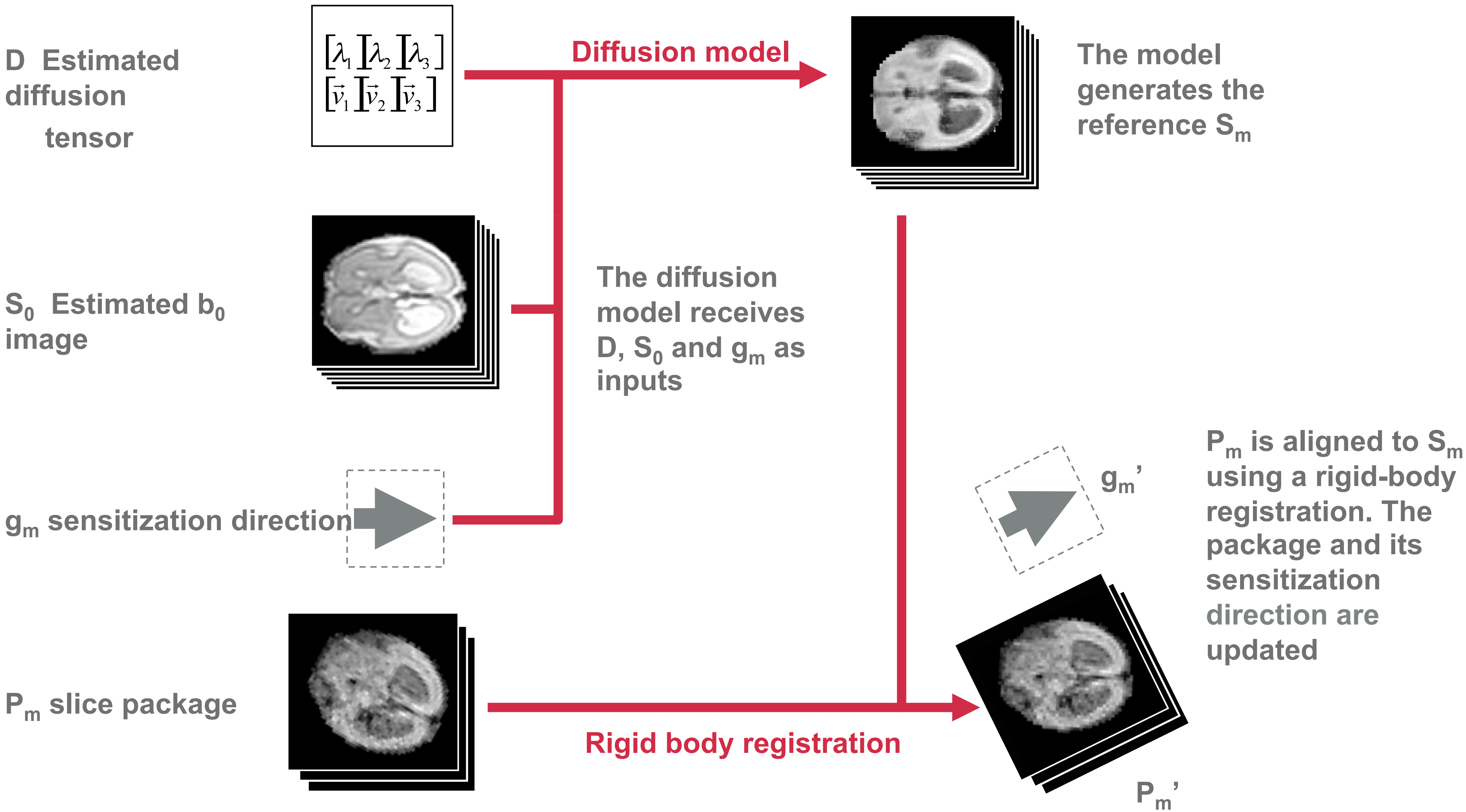
DTI-SVR registration



β_i

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Reconstruction Method

Construct forward problem expressing the actual scattered data in terms of a set of unknown diffusion tensor coefficients defined on a regular grid

$$s_{scatter} = g'(R'D_{Ana;scatter}R)g = \sum_{i=1}^{N} \beta_i g'(R'D_{Ana;regular,i}R)g$$

where $S_{scatter}$ = ln (I_i/I_0)

Invert and solve e.g. using optimization methods (such as LSQR)

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Initial study

10 fetuses scanned at the GA from 22 weeks to 34 weeks

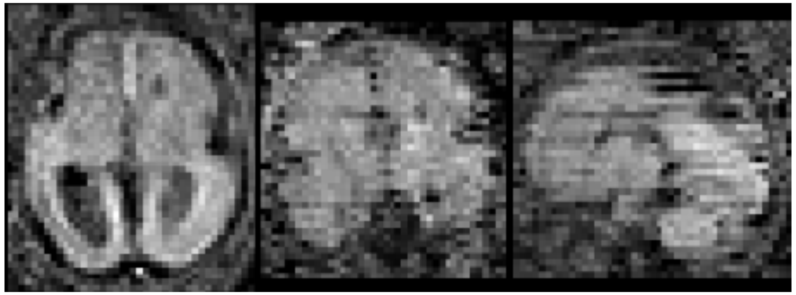
- Images are acquired using a 1.5 T scanner (Philips Achieva) with a spin echo DTI sequence:

  Image matrix: 150*150, FOV: 300 mm, b-value = 500s/mm,TR = 12s, TE = 54ms TH: 3-4 mm with minus half TH gap.

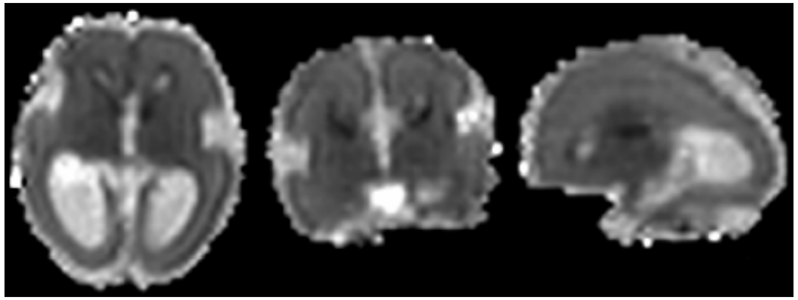
- The mother was free breathing during scanning and no sedation was used.
- Basic scanning time was 7minutes for one set of 15 direction DTI. 2-4 sets were acquired depending on patient acceptance
- Images were prepared for registration by semi-auto segmenting the fetal brain from the maternal tissues

All of datasets were successfully reconstructed in terms of Mean Diffusivity (MD), and 6 have good FA as well.

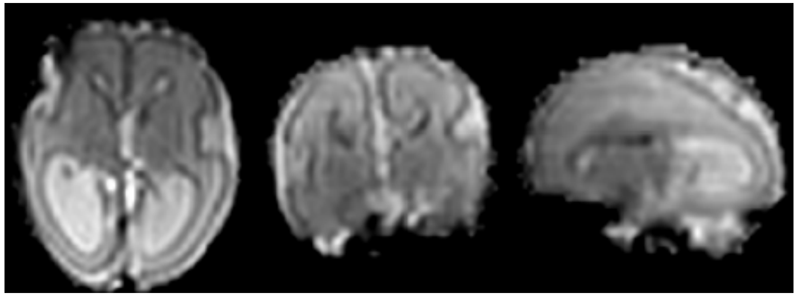
26 week old fetus



Original images



Reconstructed MD map



Reconstructed b_0 image (S_0)

Reconstructed FA map

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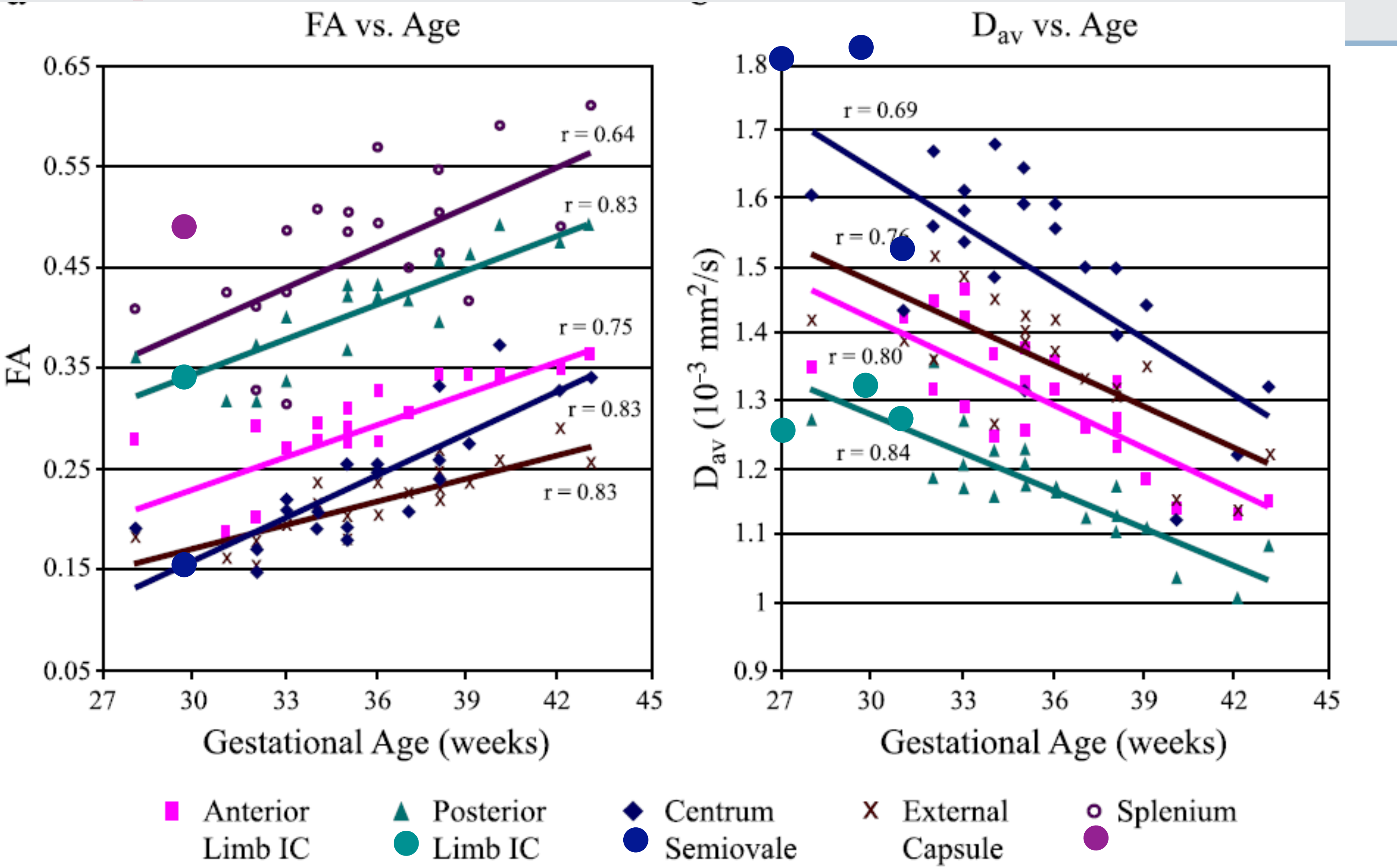
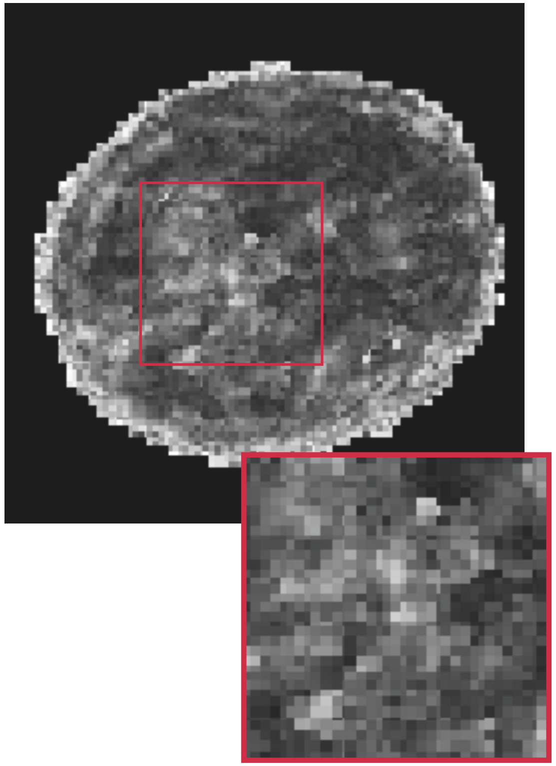
Compared to ex-utero results

Partridge *et al.* NeuroImage 2004

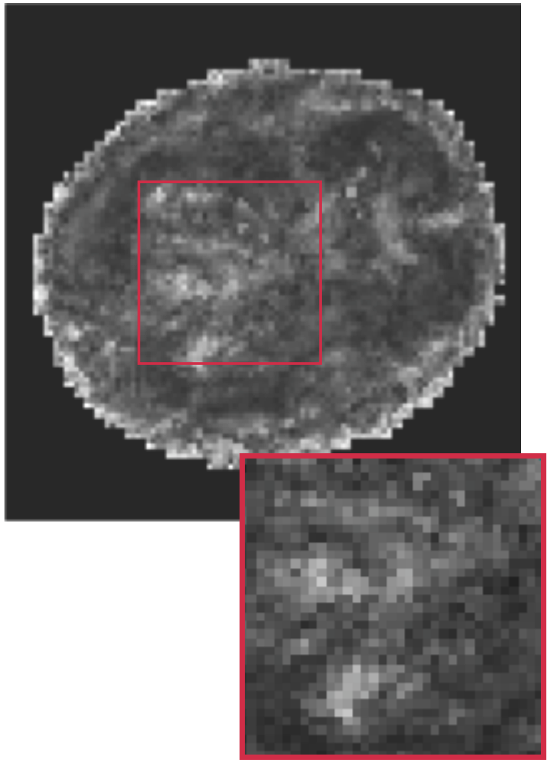


Fractional Anisothropy maps

Before corrections



After old DTI-SVR correction



After old and new DTI-SVR corrections

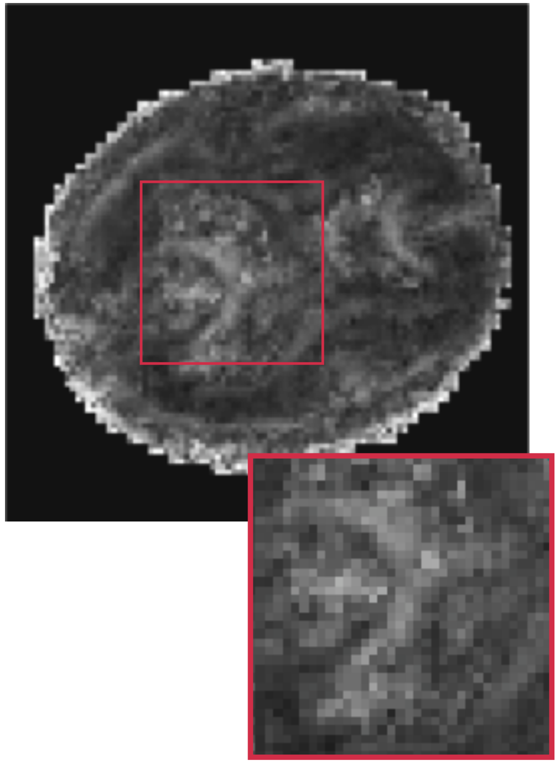
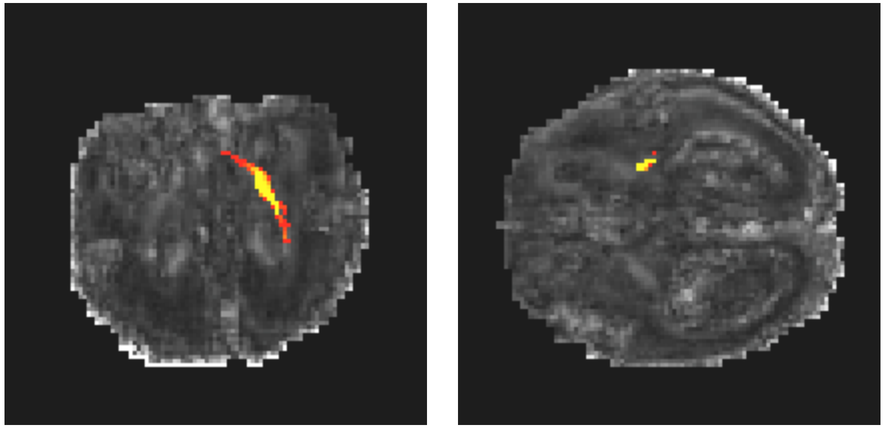


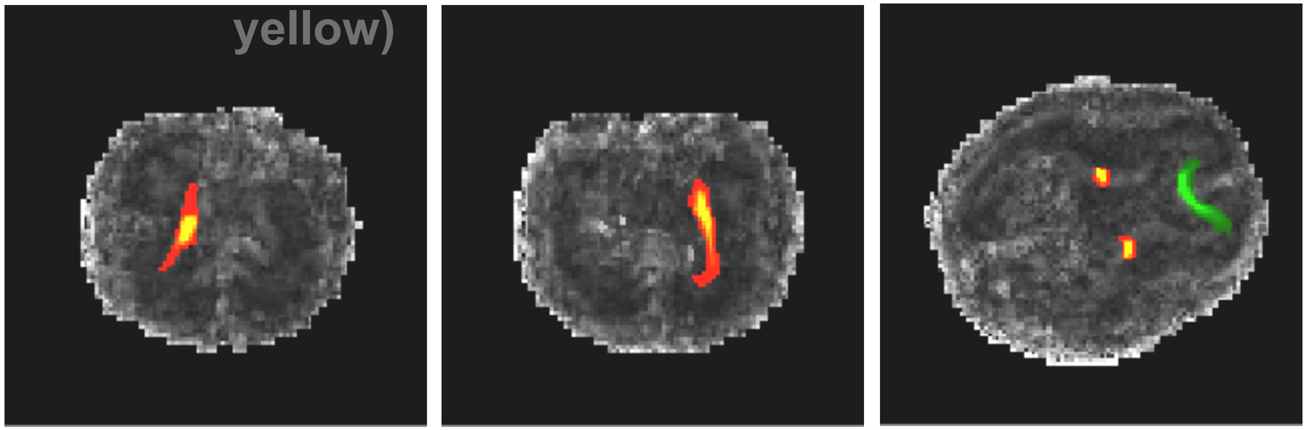
Image quality increases in the FA maps and tracts become visible

Bertelsen et al ISMRM 2009 p 3416

Tractography results using FSL- 1



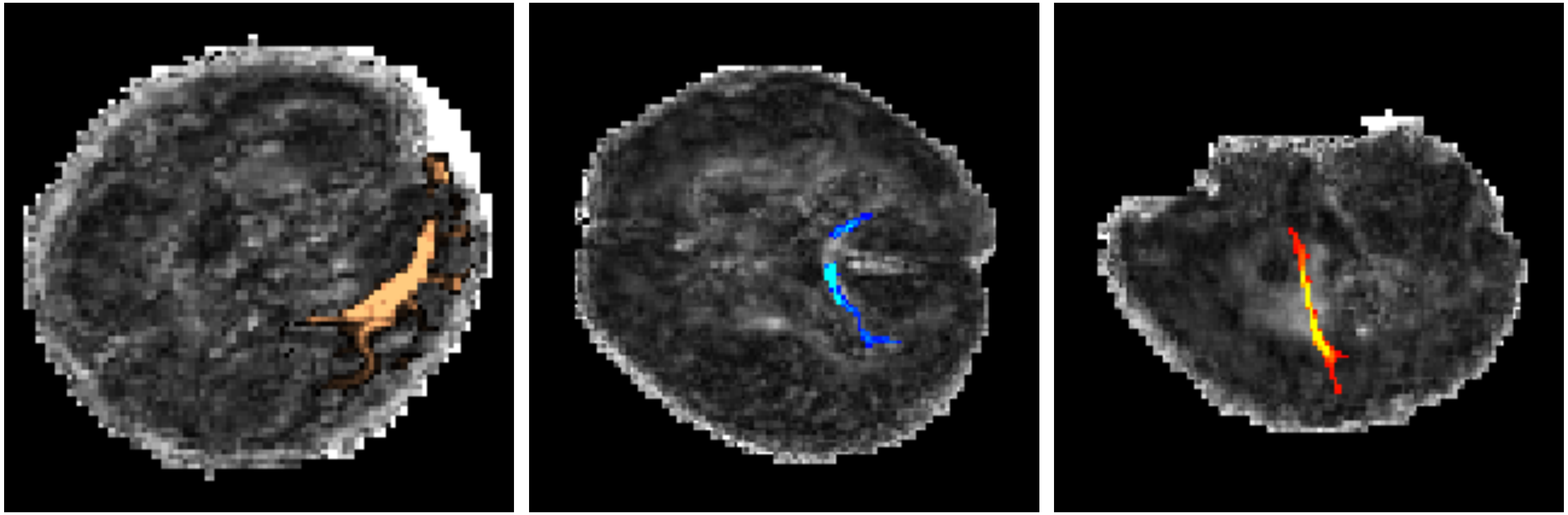
Subject 1 Corticospinal tracts (red-yellow)



Subject 2 Corticospinal tracts (red-yellow) and corpus callosum (green)

Bertelsen et al ISMRM 2009 p 3416

Tractography results using FSL- 2



Subject 3 Optic radiation

Subject 4 Corticospinal tracts (red-yellow) and splenium of the corpus callosum (blue)

Bertelsen et al ISMRM 2009 p 3416

Conclusions & Applications

- Can perform structural and diffusion imaging in moving subjects by snapshot imaging with volume reconstruction (SVR)

- T2 and T1 weighted imaging possible, DTI with full motion correction is developing

- Results consistent with ex-utero controls

- Opens up new possibilities for fetal brain research
  - e.g. cortical analysis

- Methods applicable to other brain studies where subjects cannot stay still

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