Structural neuroimaging: experience in the study of brain development

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Avec le soutien de:

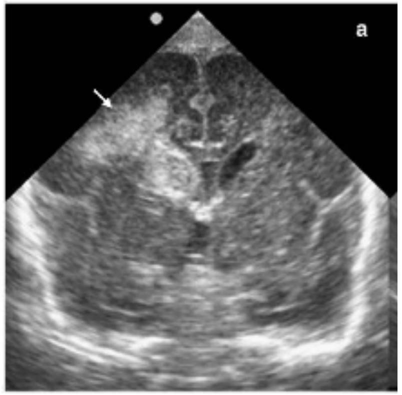
Outline

- Motivation and clinical context
- Structural MRI of fetal brain in-utero
  - Technical challenges
- Reconstruction
  - Registration and Interpolation
- Segmentation
  - Classification in a Bayesian framework and MRF priors
  - Quantitative results
- Discussion

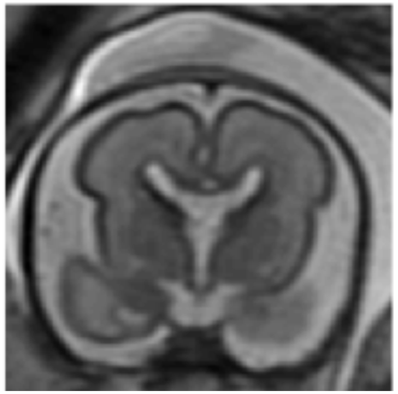
Motivation

- Fetal MRI is acquired in a clinical practice: as a complementary diagnostic tool for a precise visualization of pathologies of the 2nd and 3rd trimester.

27 weeks of gestational age (GA)



Ultrasound



MRI

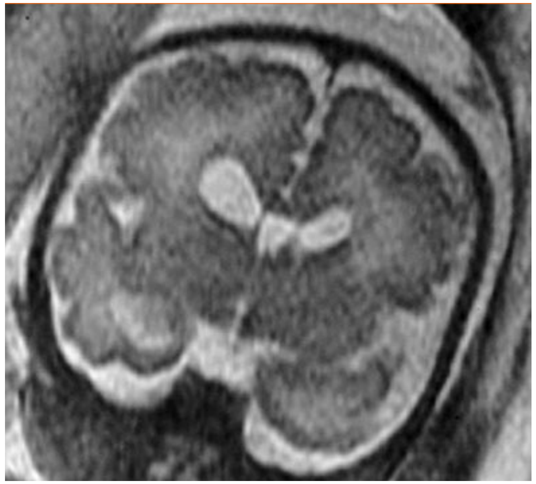
Leijser et al., Early Human Development, 2009

- Further our understanding of normal early brain development
  - Until now, largely based on studies of post-mortem brains or premature newborns
  - Fetal MRI can provide a real *in vivo* quantification of the normal developing brain

Clinical motivation

- Study of brain development:
  - Study of pre-term
  - Congenital heart disease
  - Intra-uterine growth restriction
  - Mild ventriculomegaly

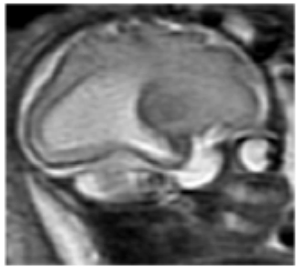
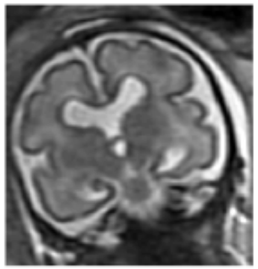
Mild ventriculomegaly



Brown et al. 2004 , www.medscape.com/

- Give parents a more accurate picture of what they can expect for their child from a neurological and developmental standpoint.
- Help in making decisions during pregnancy.

Clinical acquisition

Sagittal acquisition			
Axial acquisition			
Coronal acquisition			

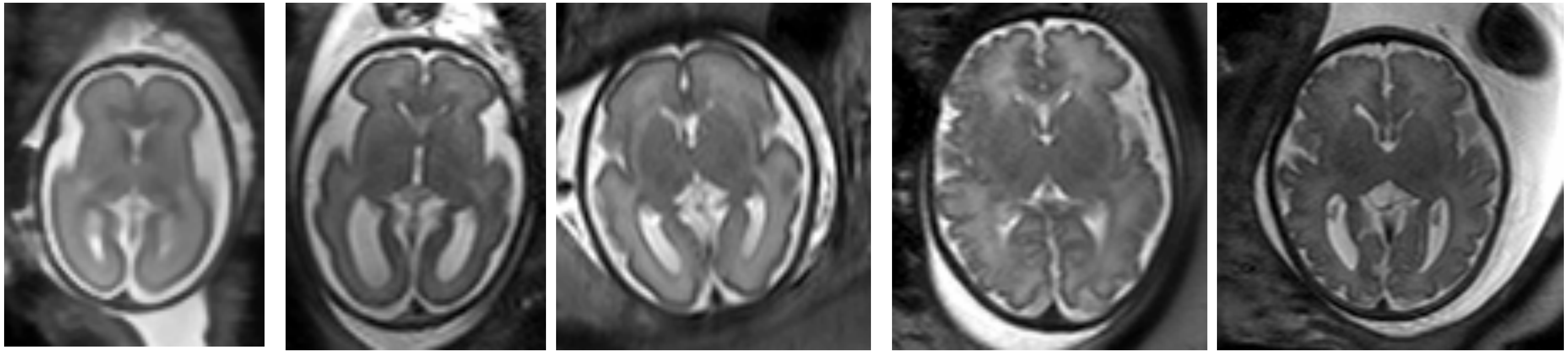
Philips 1.5 Tesla, T2-w SSFSE sequence (TR 7000 ms, TE 180 ms, FOV 40 cm, slice thickness 5.4 mm, in plane res 1.09 mm)

Fetal MRI: technical challenges

- **Motion** is an important challenge:
  - Intra-plane, inter-slice, inter-volume
  - Motion from fetus and from mother
  - Sedation helps partially
  - To avoid motion: fast acquisitions and low image resolution
  - Thus, **poor SNR, and partial volume**

Fetal MRI: technical challenges

- Rapidly changing appearance of the fetal brain:
  - In contrast intensity -> myelination
  - In morphometry -> continuous brain growth and ongoing folding



24 GA 27 GA 30 GA 33 GA 35GA

- Small data sets

As **safety** remains an open question, ethical considerations restrain the acquisition of large datasets of healthy fetuses.

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Reconstruction (I)

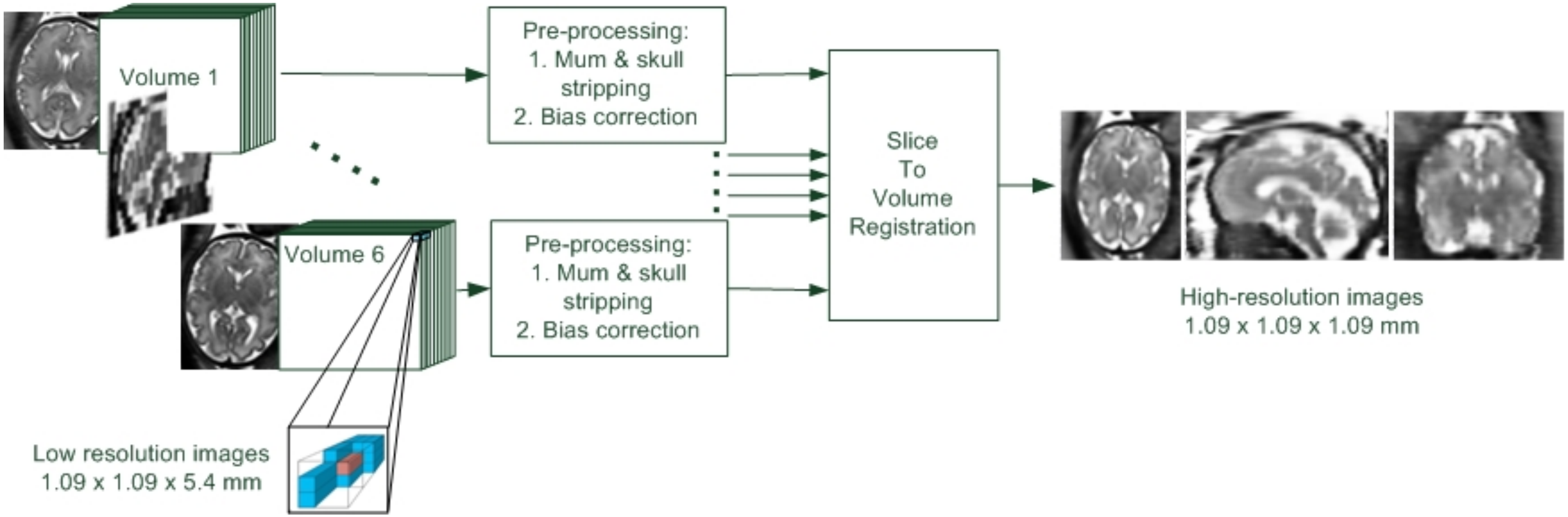
- Creating a super-resolution (SR) volume: spatial methods:
  - Observation model $\mathbf{y}_r = H_r \mathbf{x} + \mathbf{n}_r,$

y_r: LR images, r {1..n}
x: SR images
n: observed noise
H_r: motion, degradation

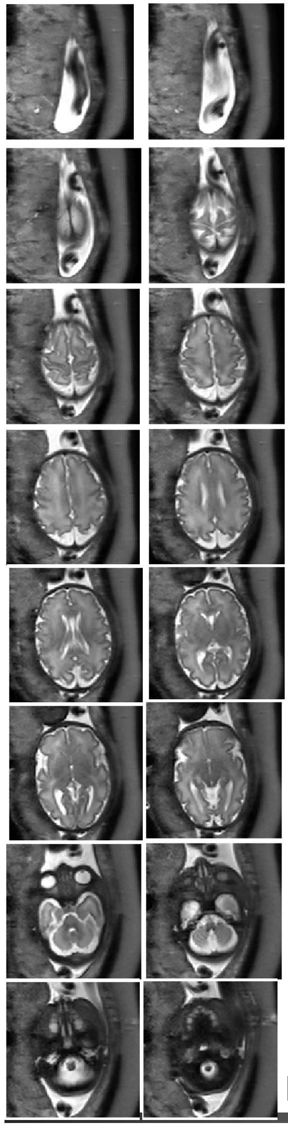
- Motion estimation
- SR reconstruction:
  - Bayesian (Gholipour et al 2009)
  - Interpolation-Registration (Rousseau et al 2006, Jiang et al 2007, Kim et al 2009)

Reconstruction (II)

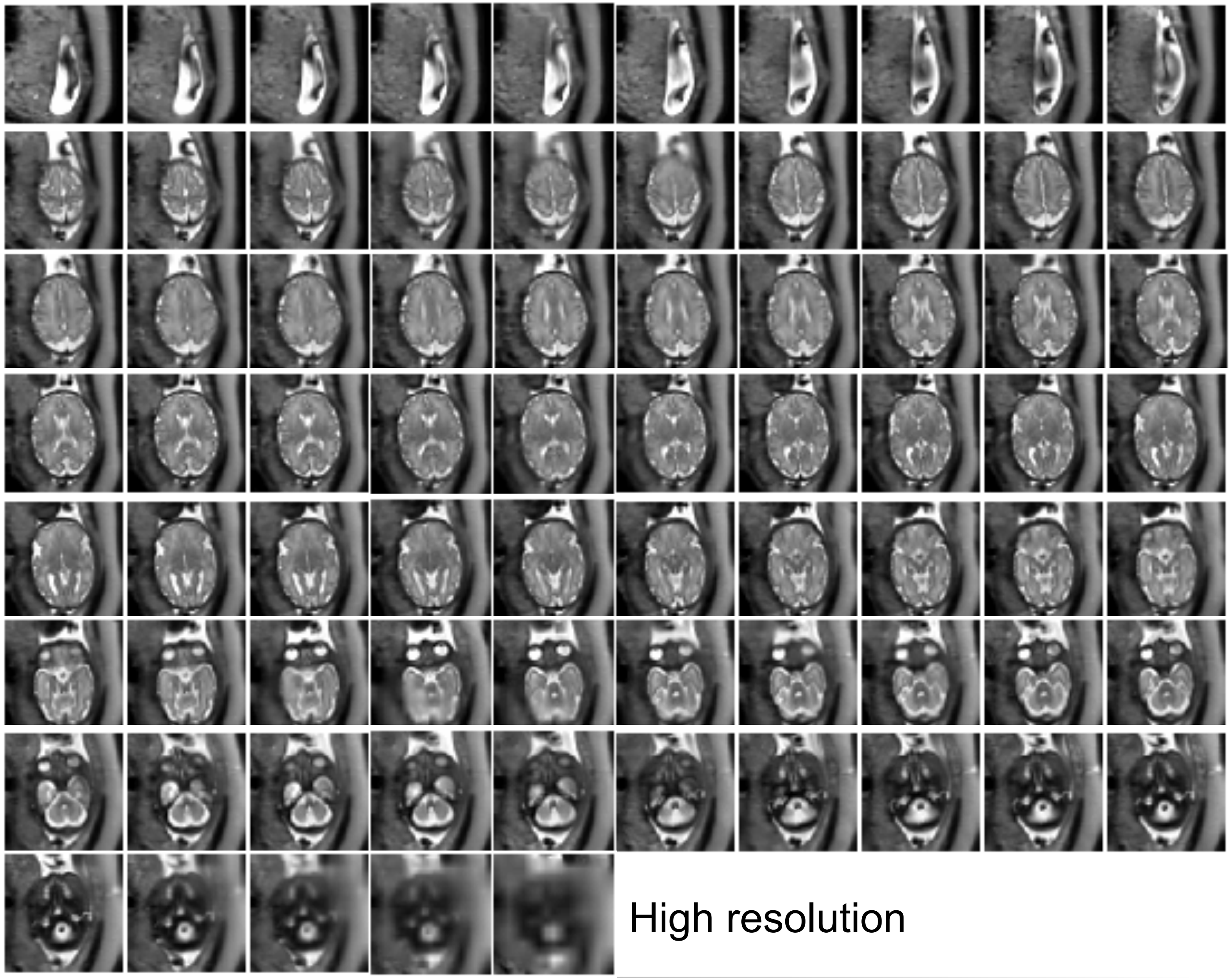
- 2D to 3D registration problem
- Scattered Data Interpolation (SDI)



High-resolution image



Low resolution



High resolution

Reconstruction of SR image

Low resolution image
(voxel size 1.09 x 1.09 x 5.4 mm)

High resolution image
(voxel size 1.09 x 1.09 x 1.09 mm)

18 slices

Fetus of 32 weeks

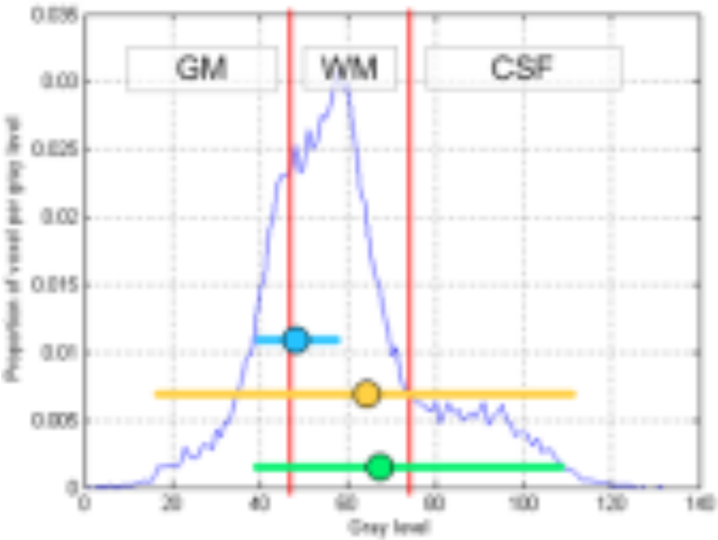
85 slices

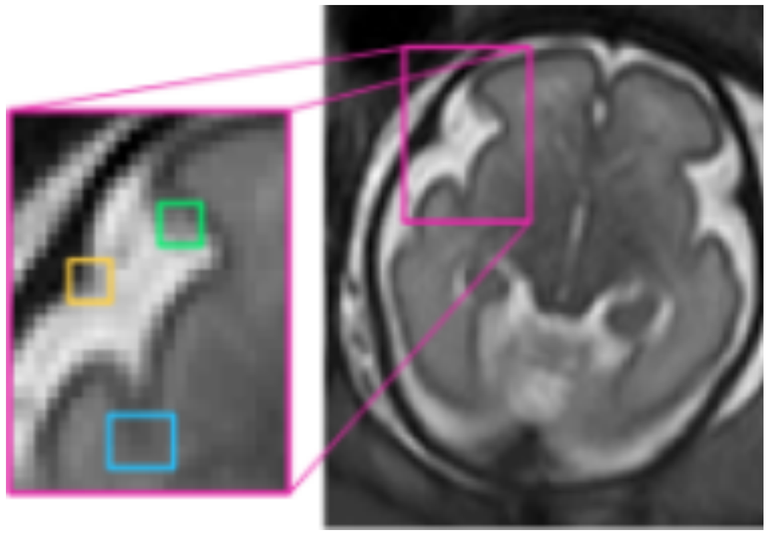
Segmentation

- Probabilistic and anatomical atlas (Habas et al 2008, 2010) -> avoid circularity risk of priors
- Data driven:
  - Bach Cuadra 2009 -> MRF priors
  - Gholipour et al 2011 -> user supervision
  - Caldairou et al 2011 -> topological model

Statistical classification of fetal brain tissue

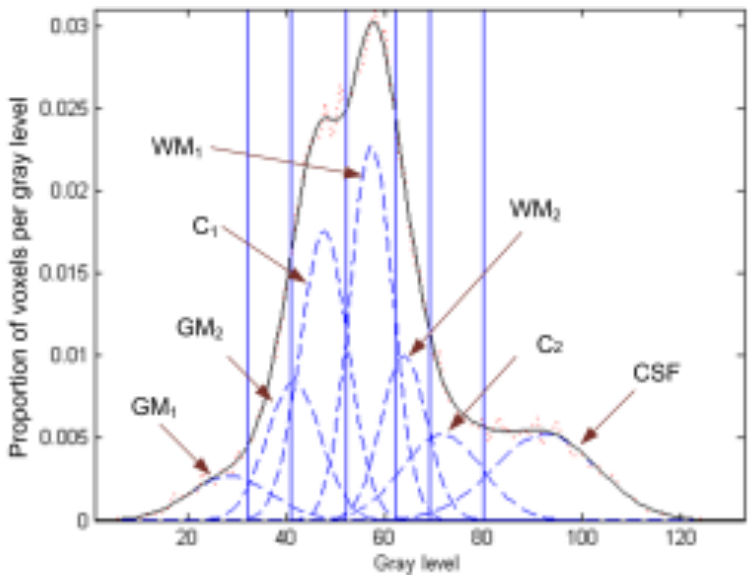
- Challenges
  - Poor spatial resolution and / or low SNR in MR images due to fast acquisitions
  - Non-homogenous brain tissues (myelination, cortical maturation)
  - Partial volume effect

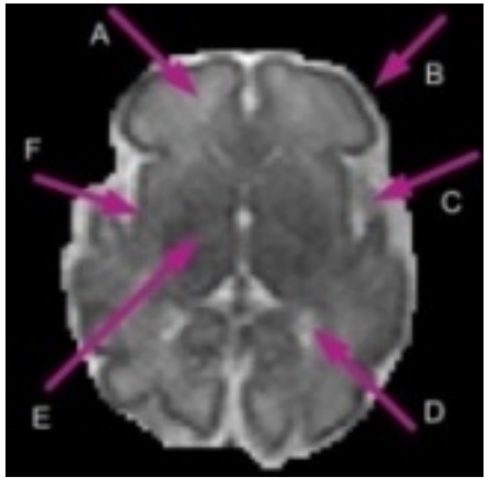


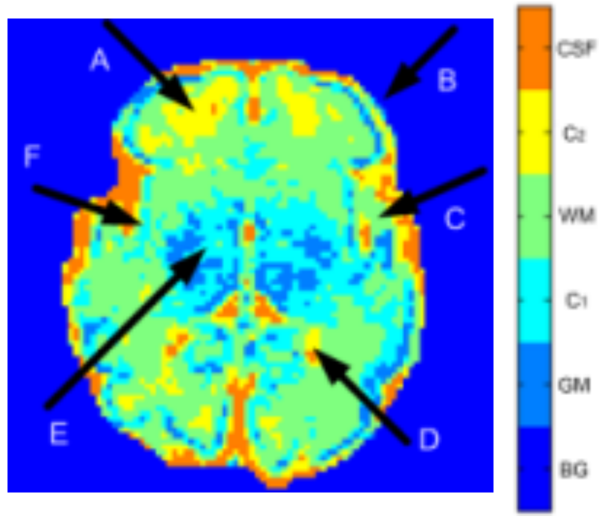


Statistical classification of fetal brain tissue

Bayesian classification after Gaussian Mixture fitting on image histogram







	Tissue	Represented by label Main, Axiliary		In Figure
True	CoGM CeGM WM CSF	GM C1 WM CSF	---- GM C2,C1 C2	--- E A D
PV	CSF+NB CSF+GM GM+WM WM+CSF	GM WM C1 C2	C1 --- --- ---	B C F ---

- Bach Cuadra et al., MICCAI 2009

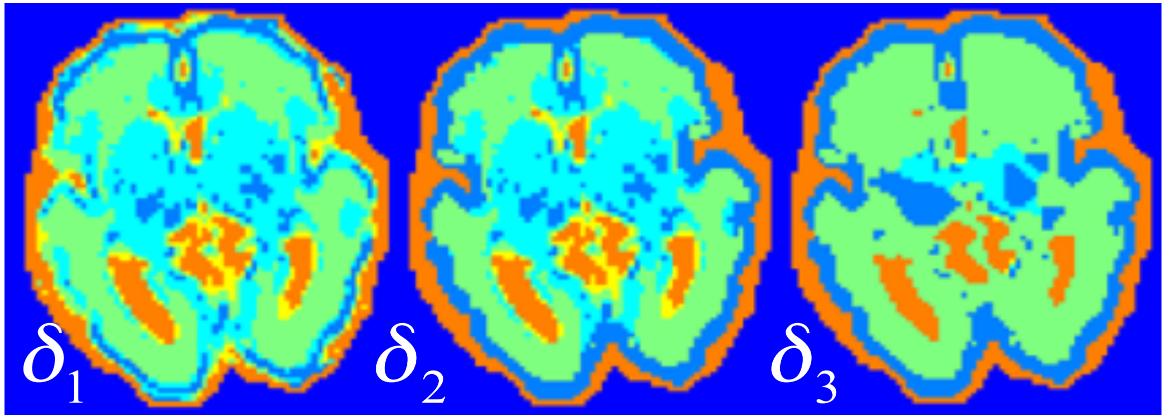
Markov Random Field model

- **Local spatial priors**
- Refining the classification with a Markov Random field as spatial distribution model, applied in 3 steps and dependent of cortical distance

$$x_i' = \max_{\forall x \in L}(U_i(x))$$

$$U_i(x) = V_i(x_i) + \sum_{j \in N_i} \frac{\delta_n(x_i, x_j)}{d(x_i, x_j)}, n = 1, 2, 3$$

  - CSF
  - Cortical gray matter
  - Central gray matter
  - White matter



MRF Energy

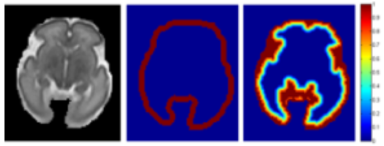
1. Remove PV of non-brain/CSF

$$\delta_1(x_i, x_j) = \begin{cases} 20 \text{ if } x_j = BG \\ 0, \text{ otherwise} \end{cases}$$

2. Reclassification of C_1 into either GM or WM

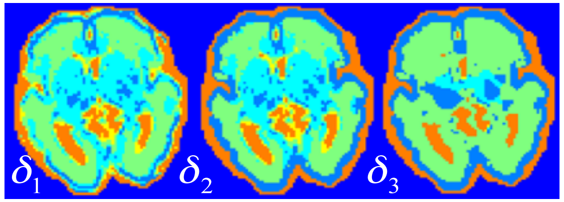
- *C_1 voxels in cortical area are PV of GM/WM -> GM*
- *Expansion of cortical CSF till GM*

$$\delta_2(x_i, x_j) = \begin{cases} 2.5 \cdot \beta_x(x_i, x_j) \cdot \text{COmask, if } x \in \{GM, CSF\} \\ 0, \text{ otherwise} \end{cases}$$

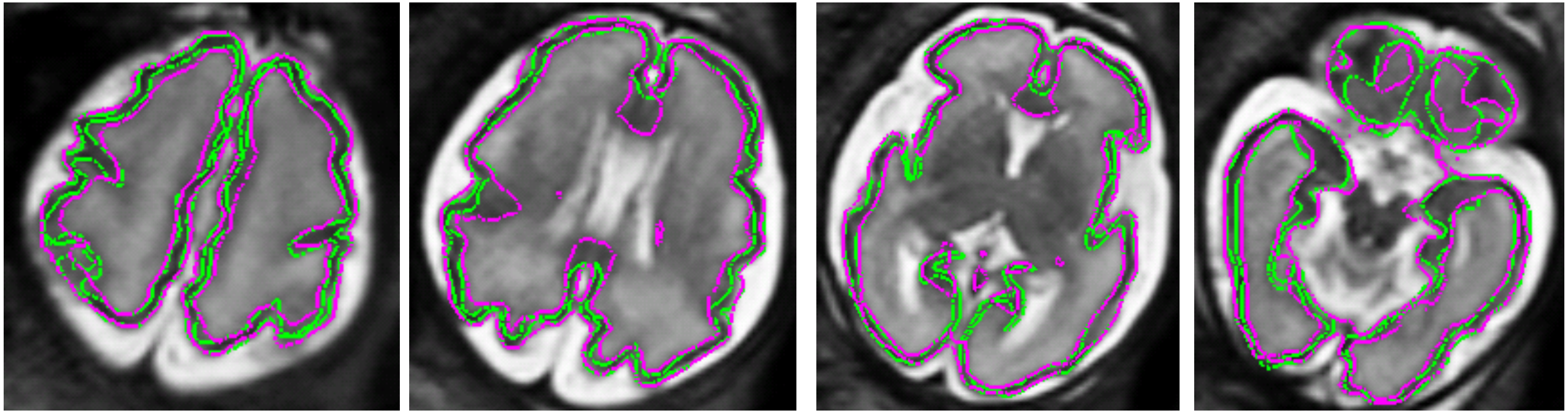


3. Reclassification of C_2 into either WM or CSF

$$\delta_3(x_i, x_j) = \begin{cases} 2, \text{ if } x_i = C_1 \text{ and } x_j = GM \\ 3, \text{ if } x_i = C_1 \text{ and } x_j = WM \\ 3, \text{ if } x_i = C_2 \text{ and } x_j = WM \\ 2, \text{ if } x_i = C_2 \text{ and } x_j = CSF \\ 0, \text{ otherwise} \end{cases}$$



Intermediate results

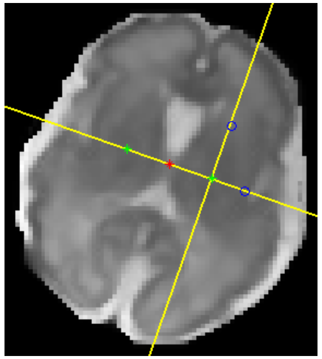


Contour extracted after statistical classification

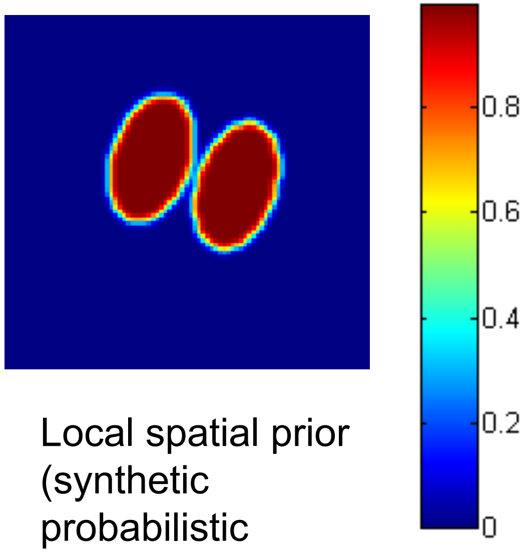
Manual segmented contour

Fetal brain basal ganglia segmentation

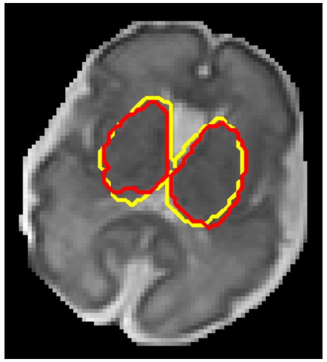
Areas where cortical and central GM are touching



Manual initialization:
3 points:
center of BG
minor and major axis.



Local spatial prior (synthetic probabilistic maps)

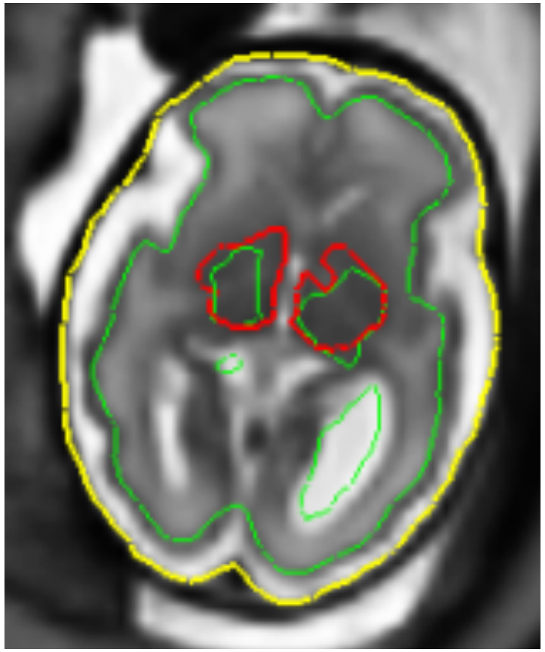


- expert (manual) segmentation
- automated segmentation

- Bach Cuadra et al., ISMRM 2010

3D Surface reconstruction

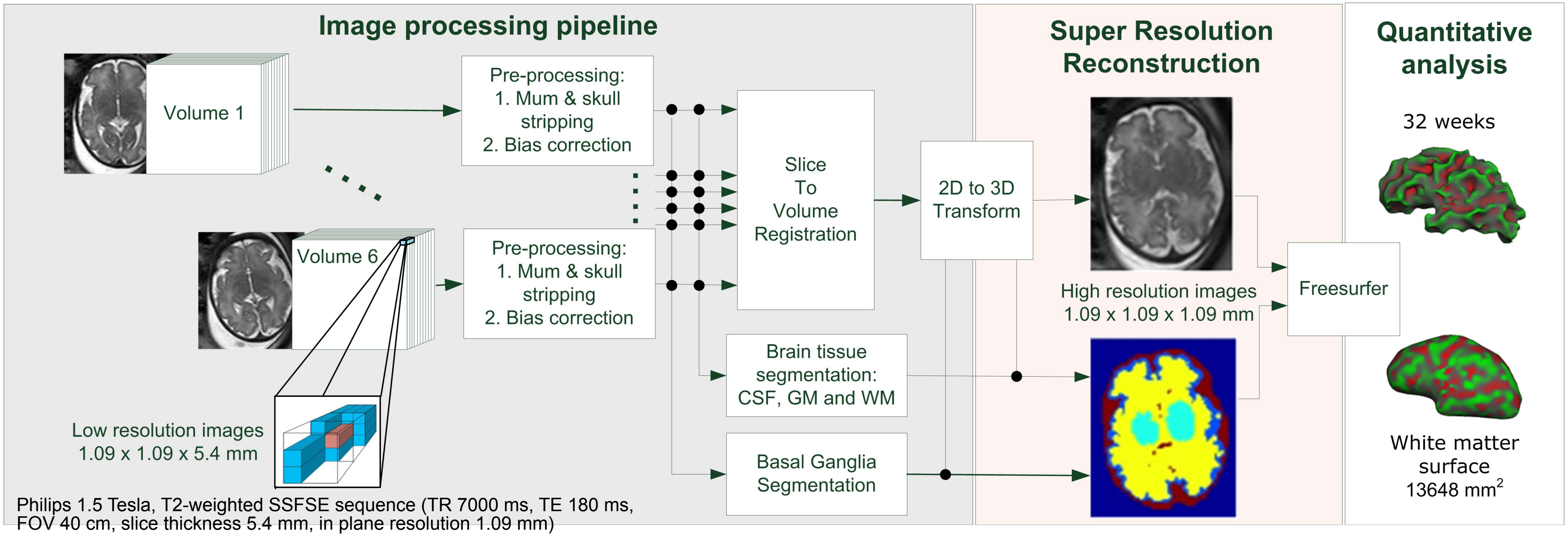
- Import the initial segmentation in Freesurfer
- Optimization of the cortical surface according to the gray / white intensity gradient in 3D
- Incl. Topology correction (geometrically accurate 3D representation of the cortex)



Input surfaces (volumes) for Freesurfer:
- brain mask
- GM/WM interface
- basal ganglia segmentation

http://surfer.nmr.mgh.harvard.edu/

Quantitative image analysis of in-utero fetal MRI



Philips 1.5 Tesla, T2-weighted SSFSE sequence (TR 7000 ms, TE 180 ms, FOV 40 cm, slice thickness 5.4 mm, in plane resolution 1.09 mm)

	WM		Basal		Cortical GM		CSF		ICV		Cortical Area	Global GI	Mean curvature	Positive curvature
GA (SA)	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var				
29	873,681	8,184 (9%)	6,021	538 (9%)	65,645	2541 (4%)	43,635	3484 (8%)	203,540	6423 (3%)	21,116	1.16	-0.0883	0.2694
29.4	129,477	4,870 (4%)	8,068	1138 (14%)	61,418	5871 (10%)	76,882	2132 (3%)	270,701	2112 (1%)	25,411	1.12	-0.0966	0.2645
31.5	157,192	12,130 (8%)	12,428	2634 (21%)	68,790	13,972 (20%)	54,670	3152 (6%)	294,431	2879 (1%)	32,679	1.19	-0.0864	0.3361

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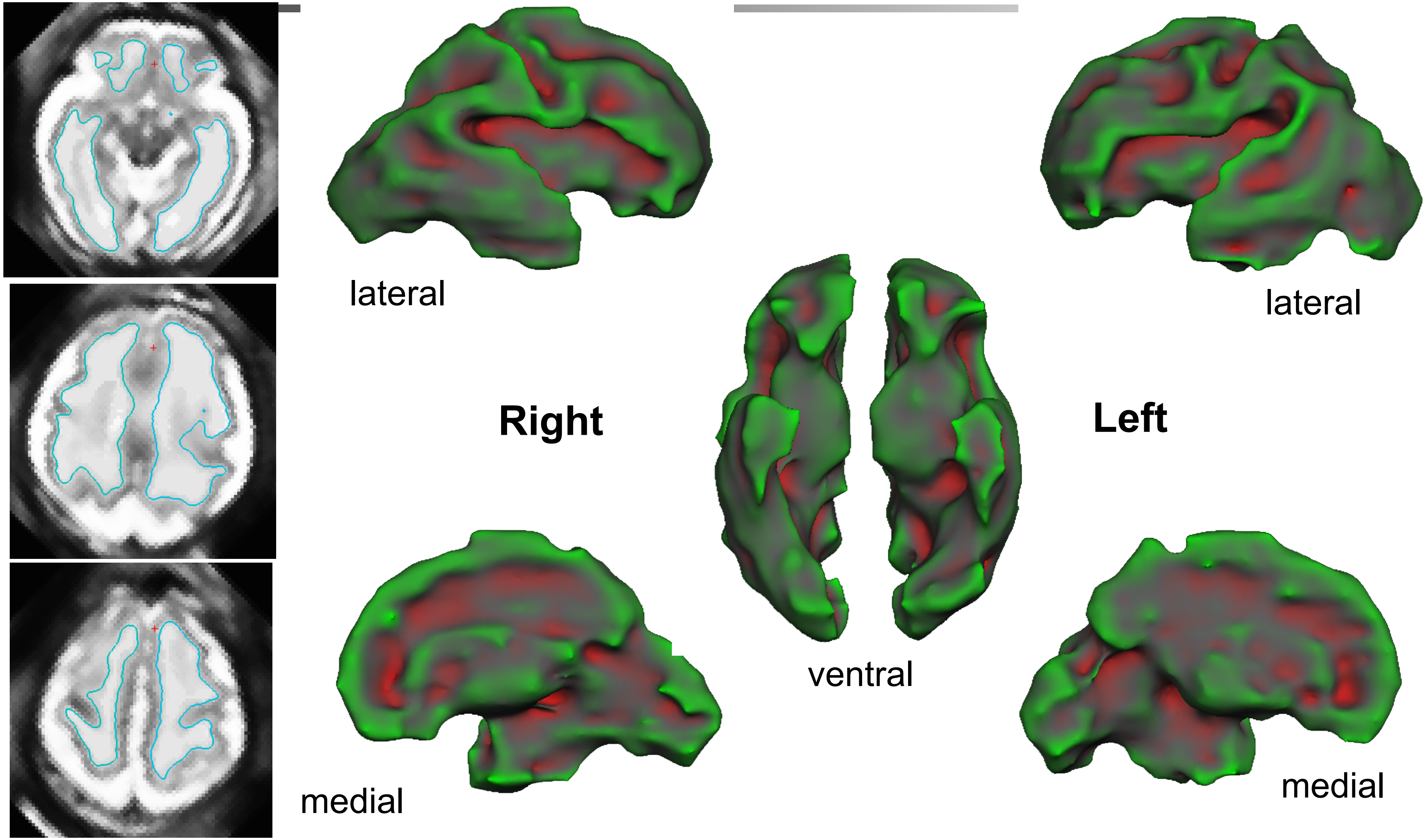
Surfaces reconstruction: 29 weeks



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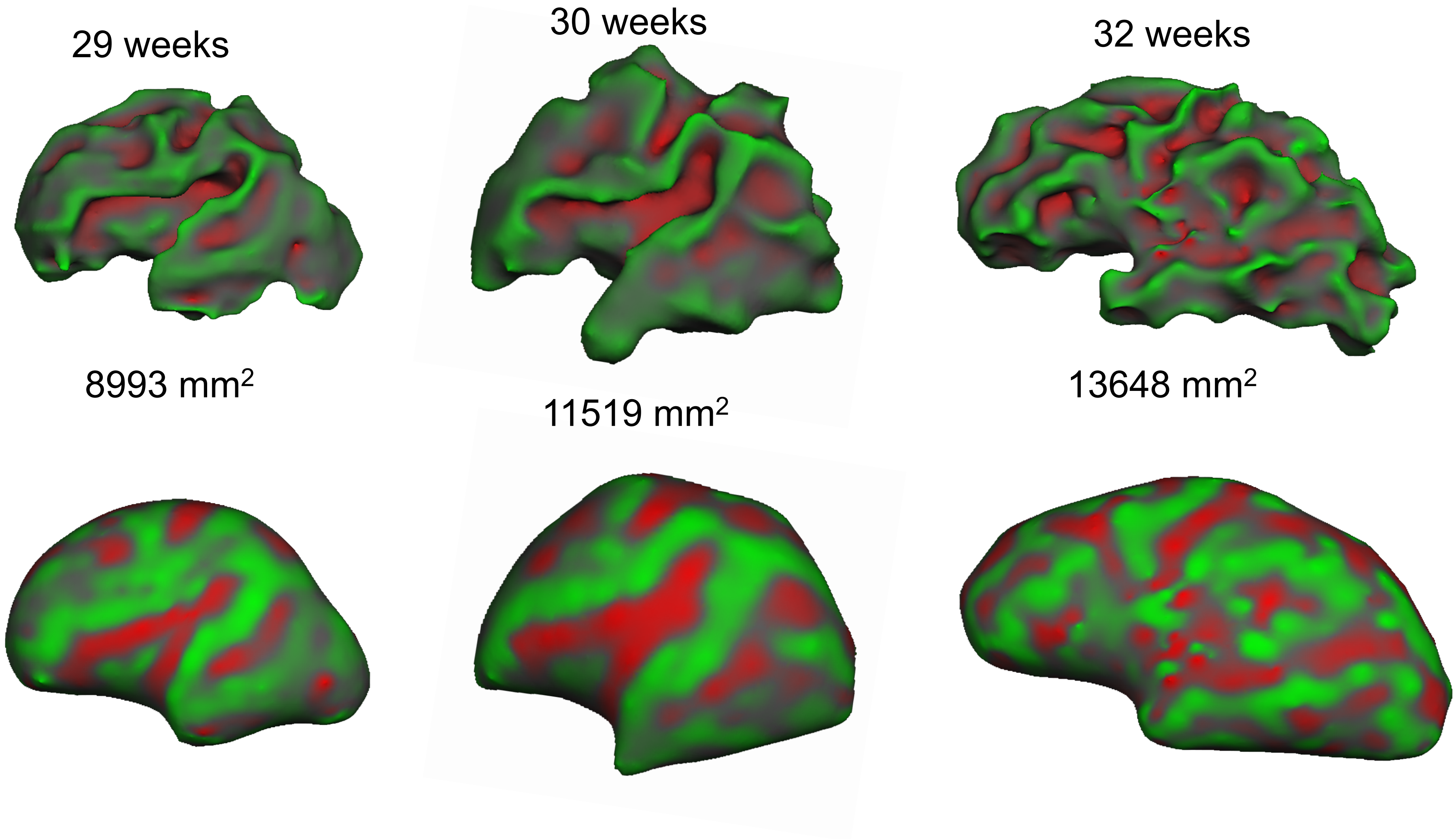
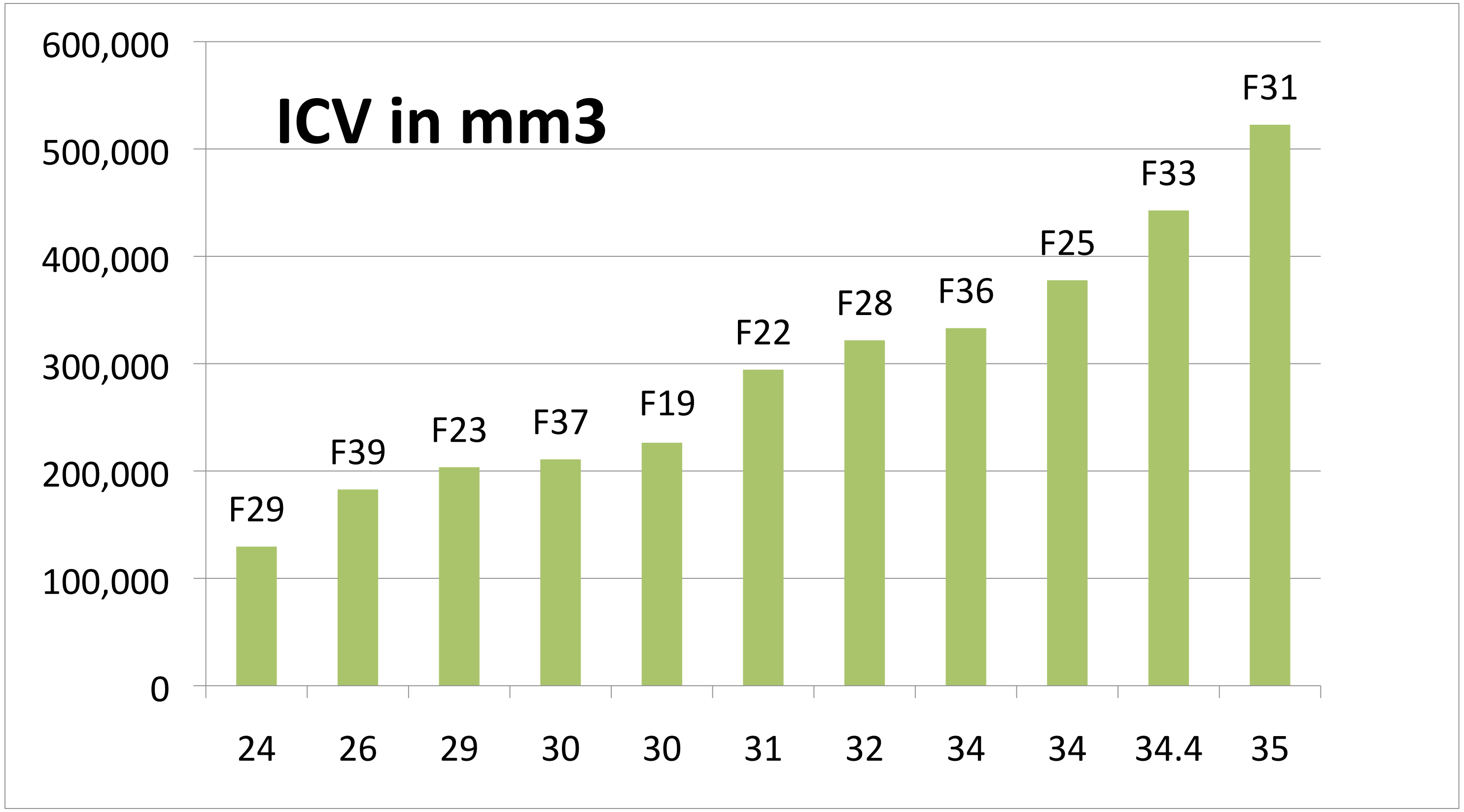
Preliminary results: GM/WM interface, WM volume



Preliminary results: ICV volumetry

- 11 fetuses
- 24 to 35 weeks



Gestational Age (in weeks)

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Discussion

- Methodological questions:
  - Improvement of high-resolution image reconstruction
  - Need for reducing user interaction: mainly on surface extraction
  - Validation with echographic measures
- Clinical questions:
  - Quantify subtle deviations from normal brain development through cortical folding studies-> gyration
  - Provide quantitative norms for clinical purpose
  - Inclusion of other MR Diffusion Imaging for anatomical connectivity analysis

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2011

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In preparation

M. Bach Cuadra, G. Bonanno, A. Andre, L. Guibaud, S. Eliez, J.-P. Thiran, M. Schaer, 'Automated segmentation of magnetic resonance images of the fetal brain for developmental studies'.