FOETUSES AND PREGNANT WOMEN MODELLING USING A COMPUTER GRAPHICS APPROACH FOR DOSIMETRY STUDIES

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Orange Labs R&D

, Workshop on Anatomical Models, 16-17 june 2009

Electromagnetic fields

- Topics: Studying the interaction between EM waves from cellular phones or WiFi systems and the tissues within the human body.

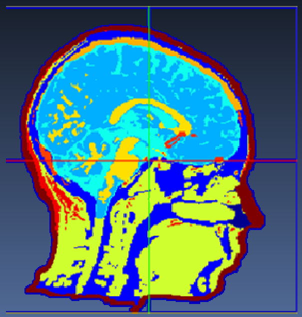
- With new technologies and habits:
  - Exposure of children and foetuses has become an important question (WHO).

- To assess exposure within the body, we need:
  - Numerical simulations (dosimetry)
  - Realistic human models of adults, children, foetuses…

Dosimetry: Numerical methods

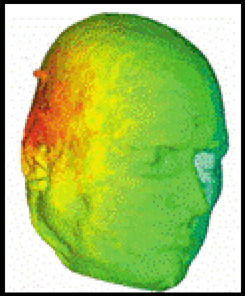
- Over the past 15 years, several studies have been performed:
  - Numerical methods for simulation of EM waves propagation in human tissues.
  - Creation of head and whole body models.

- Dosimetry simulations get faster and more complex:
  - FDTD discretization methods.
  - GPU-based implementations.
  - Multi-core processors.
  - Head model with 1 mm resolution: 9 millions of cells (10 minutes for running).
  - Whole body with 2mm resolution: 60 millions of cells (2h of running times).



Dosimetry: Exposure computation

- Physical values: E, H but also the specific absorption rate (SAR).



- The SAR:
  - characterizes the power deposited in tissues
  - quantifies the absorbed power per mass unit ($W.kg^{-1}$)
  - is often averaged over the whole body or over a small mass (1 or 10 g)
  - is linked to the electric field.

Dosimetry: SAR measure

$$SAR = \frac{d\left(\frac{dW}{dm}\right)}{dt}$$

- **Energy absorbed** (dW)
- **Mass** (dm)
- **Time** (dt)

Dosimetry: SAR measure

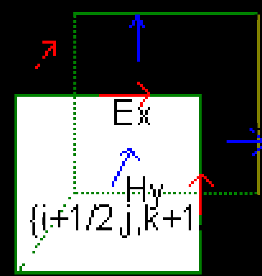
$$SAR = \frac{\sigma E^2}{2\rho}$$

where

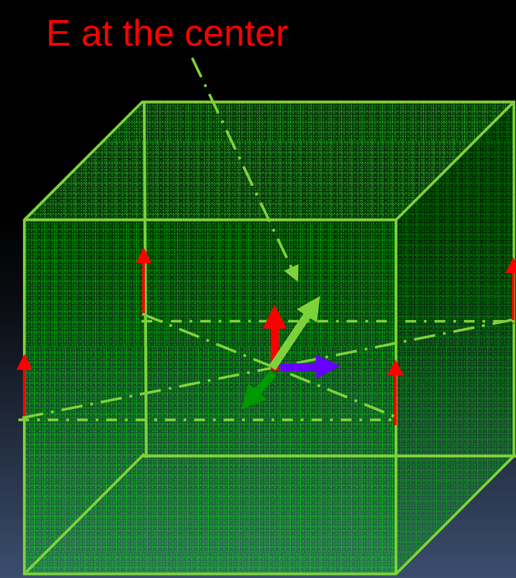
- σ is the sample electrical conductivity (S.m^{-1})
- ρ is the mass density (kg.m^{-3})
- *E* is the spatial magnitude of the electric field (V.m^{-1}).

Dosimetry: Numerical Methods

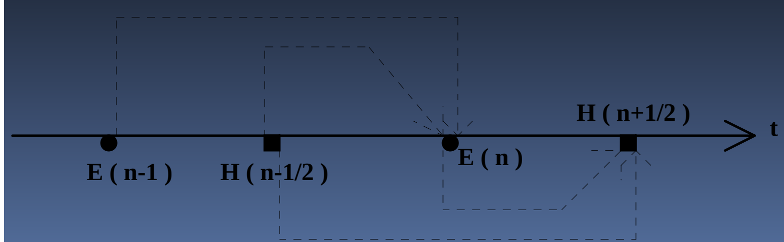
- The Maxwell Partial Differential equations estimated via finite differences



- The tissues are modeled with voxels
- Finite Differences in Time Domain (FDTD)

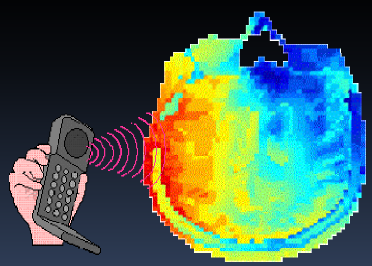


$$\frac{\partial E}{\partial t} = \mu \frac{\partial H}{\partial z} \Rightarrow \frac{E^{n\Delta t}_{i\Delta x} - E^{n\Delta t}_{(i+1)\Delta x}}{\Delta x} = \mu \frac{H^{(n-1/2)\Delta t}_{(i+1/2)\Delta x} - H^{(n+1/2)\Delta t}_{(i+1/2)\Delta x}}{\Delta t}$$



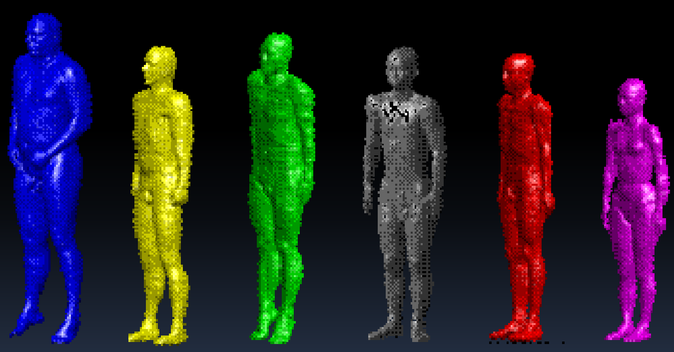
Dosimetry: resolution needed

- SAR approximation:
  - 1 g of tissues is a cube having edges of 1cm.
  - 2 mm resolution to estimate SAR in tissues is acceptable.



Human Body Models: Background

- Only few whole-body models of adults were proposed.
- Even fewer children models…
- Foetus models are rare.
- Difficulties:
  - Be realistic.
  - Be representative.
  - Based on real data…



Human Body Models: Background

- Spatial resolution needed for models:
  - 1 g of tissues is a cube having edges of 1cm
  - Numerical method grid size constraint is λ/10 ….. but model resolution and grid size are different constraints
  - 2 mm resolution to estimate SAR in tissues is acceptable

Pregnant Women Models: Previous work…

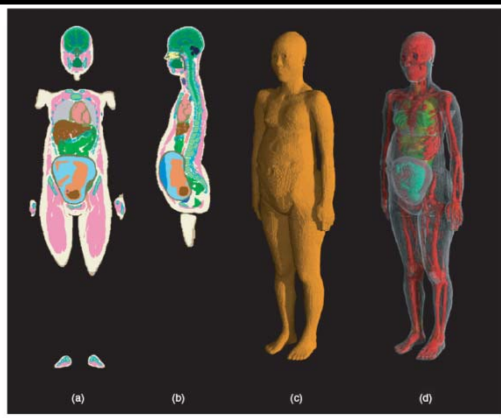
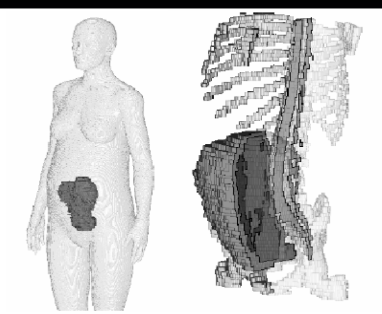


Figure 5. Developed anatomically realistic model of a pregnant woman: (a) midcoronal section image, (b) midsagittal section image, (c) body surface image, (d) tissue-enhanced image.

IOP Publishing — Physics in Medicine and Biology
Phys. Med. Biol. **52** (2007) 6731–6745 doi:10.1088/0031-9155/52/22/012

An anatomically realistic whole-body pregnant-woman model and specific absorption rates for pregnant-woman exposure to electromagnetic plane waves from 10 MHz to 2 GHz

Tomoaki Nagaoka[1], Toshihiro Togashi[2], Kazuyuki Saito[3], Masaharu Takahashi[3], Koichi Ito[4] and Soichi Watanabe[1]



(a) (b)

Figure 1. (a) Fetal soft tissue inside the full body model and (b) the fetal soft tissue and skeleton, the placenta and the uterus.

Institute of Physics Publishing — Physics in Medicine and Biology
Phys. Med. Biol. **52** (2007) 879–888 doi:10.1088/0031-9155/52/4/001

Fetal exposure to low frequency electric and magnetic fields

R Cech, N Leitgeb and M Pediaditis

Pregnant Women Models: RPI

IOP Publishing — Physics in Medicine and Biology

Phys. Med. Biol. 52 (2007) 7023–7044 — doi:10.1088/0031-9155/52/23/017

A boundary-representation method for designing whole-body radiation dosimetry models: pregnant females at the ends of three gestational periods—RPI-P3, -P6 and -P9

X George Xu[1,2,4], Valery Taranenko[1], Juying Zhang[1] and Chengyu Shi[3]

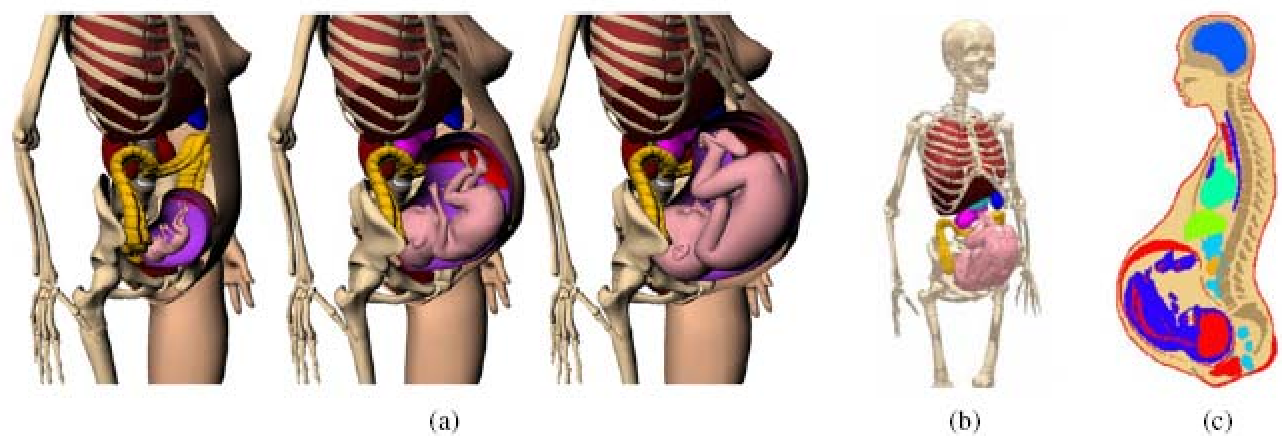
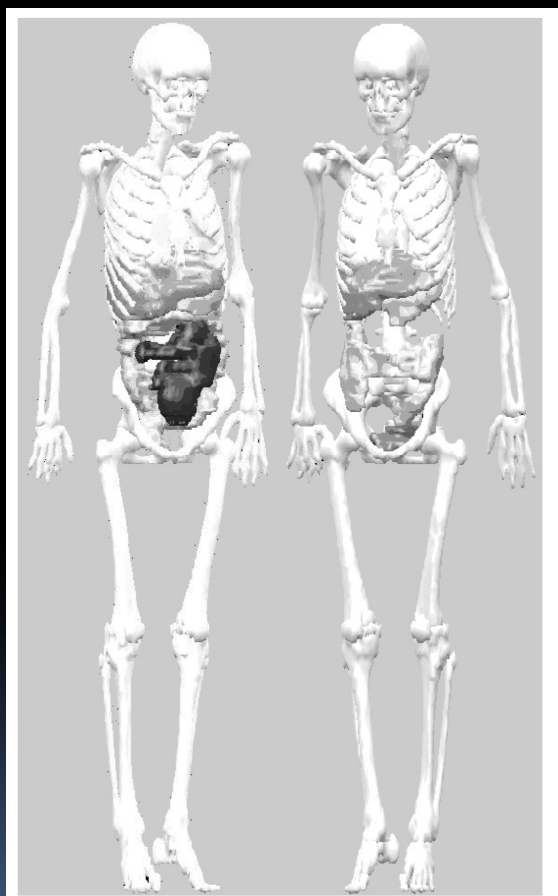


Figure 5. The finalized RPI-P models. (a) Rendering of 3D models of RPI-P3, -P6 and -P9 (from left to right) plotted from Rhinoceros, (b) rendering of the voxelized RPI-P9 model before translated into the MCNPX, (c) a direct MCNPX geometry plot showing a cross-section view of the 3 mm voxel model of the RPI-P9 implemented for Monte Carlo radiation transport calculations. Visual inspections allow the anatomical geometries to be verified.

Pregnant Women Models: KATJA



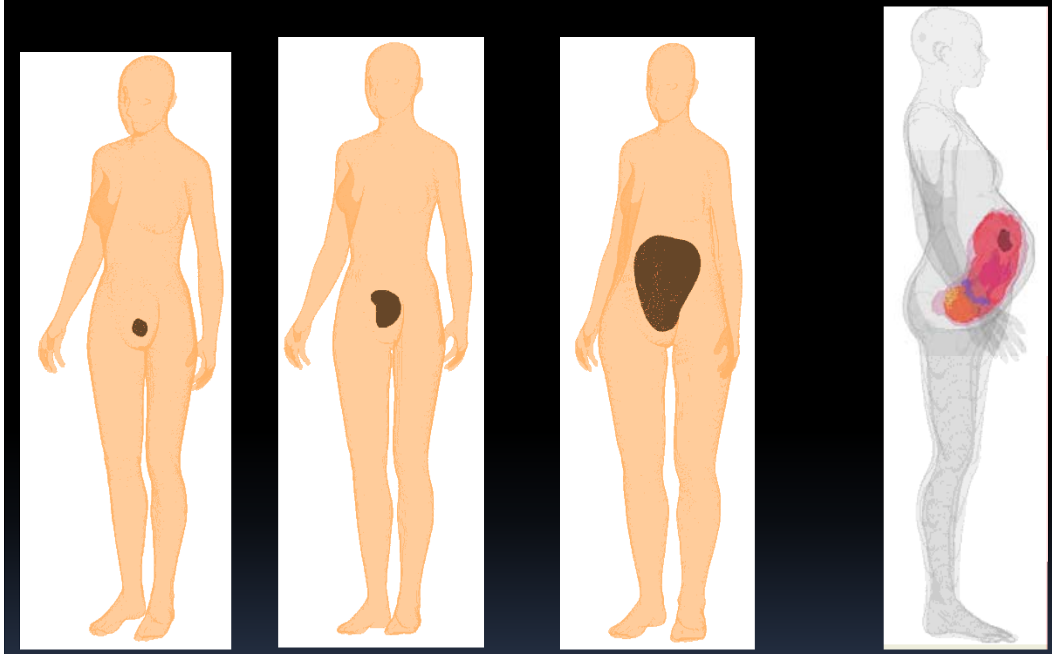
Pol J Med Phys Eng. 2008;14(1):13-19.
PL ISSN 1425-4689
doi: 10.2478/v10013-008-0002-4
website: http://www.pjmpe.waw.pl

Janine Becker, Maria Zankl, Ute Fill,
Christoph Hoeschen

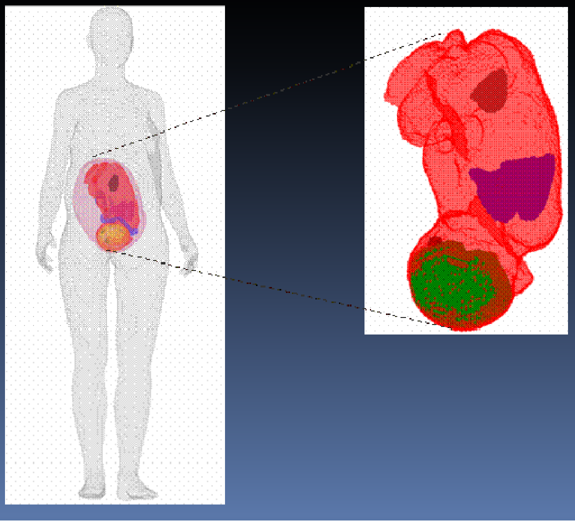
Katja — the 24th week of virtual pregnancy for dosimetric calculations

The woman has 153 organs and the foetus 18. The resolution of the voxel model Katja is $1.775 \times 1.775 \times 4.84$ mm^3. To the day, this is the most segmented foetus model in the literature. Unfortunately the only bones inside the model are spine and skull because it was segmented from a MRI scan where bones are hardly visible. The

Pregnant Women Models: Telecom ParisTech..



9 weeks 13 weeks 30 weeks 34.5 weeks



Pregnant Women Models: Medical Images

- 3D ultrasound (US) images
  - Port Royal and Beaujon hospitals (Paris, France).
  - 18 data sets.
  - Embryos at different gestational ages during the first trimester.
  - Spatial resolution: isotropic & sub-millimetric.
- 3D MRI images
  - Saint Vincent de Paul hospital (Paris, France).
  - 22 datasets.
  - Large field of view, fast acquisition
  - Foetus have 30 to 34 WA.
  - Spatial resolution: $1\times1\times4mm^3$.

Pregnant Women Models: Utero-foetal unit segmentation

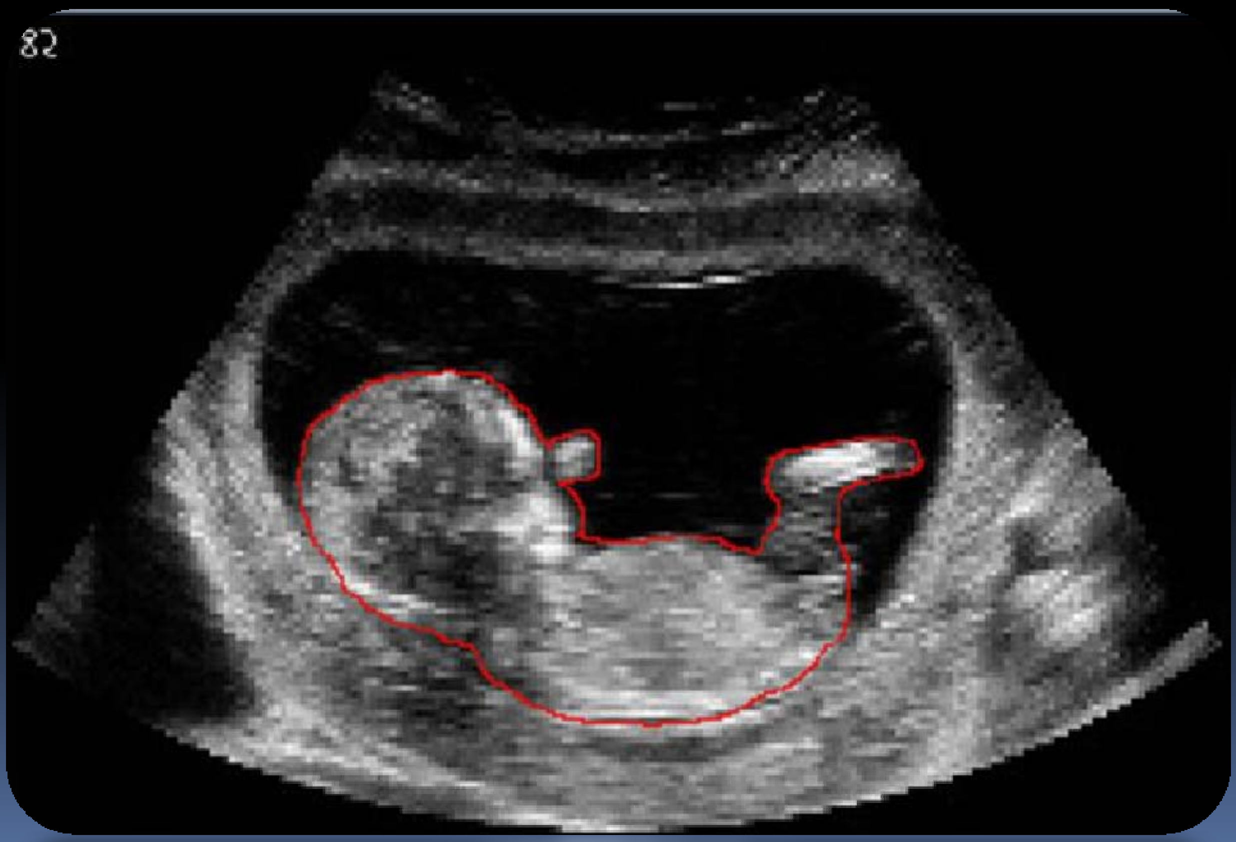
- Automatic segmentation:
  - Statistical distributions of intensities integrated in a deformable model (US).
  - Morphological information and spatial positioning of the structures (MRI)

- Manual segmentation:
  - Free-software tools:
    - MIPAV (http://mipav.cit.nih.gov/)
    - Slicer (www.slicer.org)

Anquez J, Angelini E, Bloch I (2009) "Automatic segmentation of head structures on fetal MRI". ISBI'09, Boston, USA,.

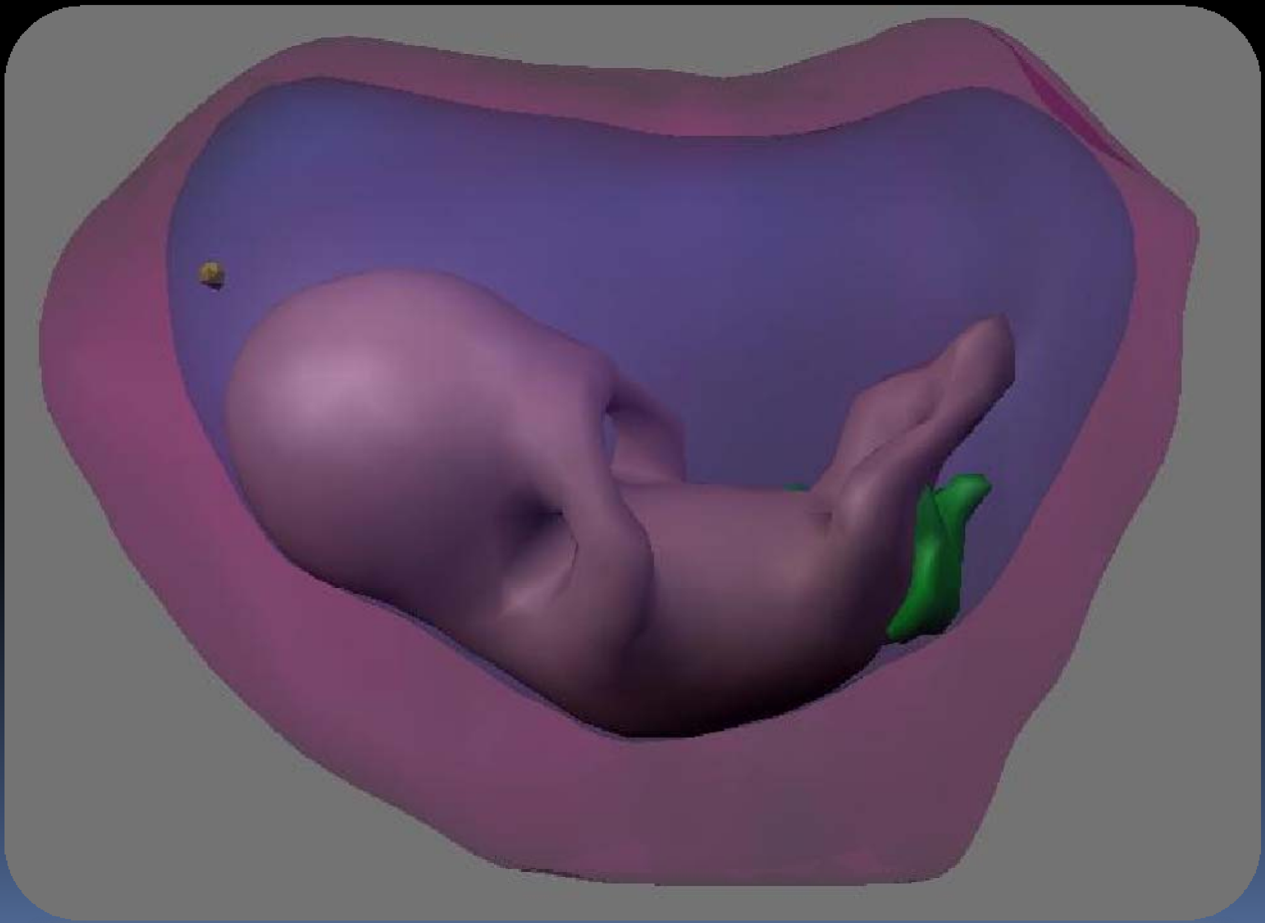
Anquez J, Angelini E, Bloch I (2008) "Segmentation of Fetal 3D Ultrasound Images based on Statistical Prior and Deformable Model". ISBI'08 pages 17-20, Paris, France

Pregnant Women Models: Segmentation on 3DUS data



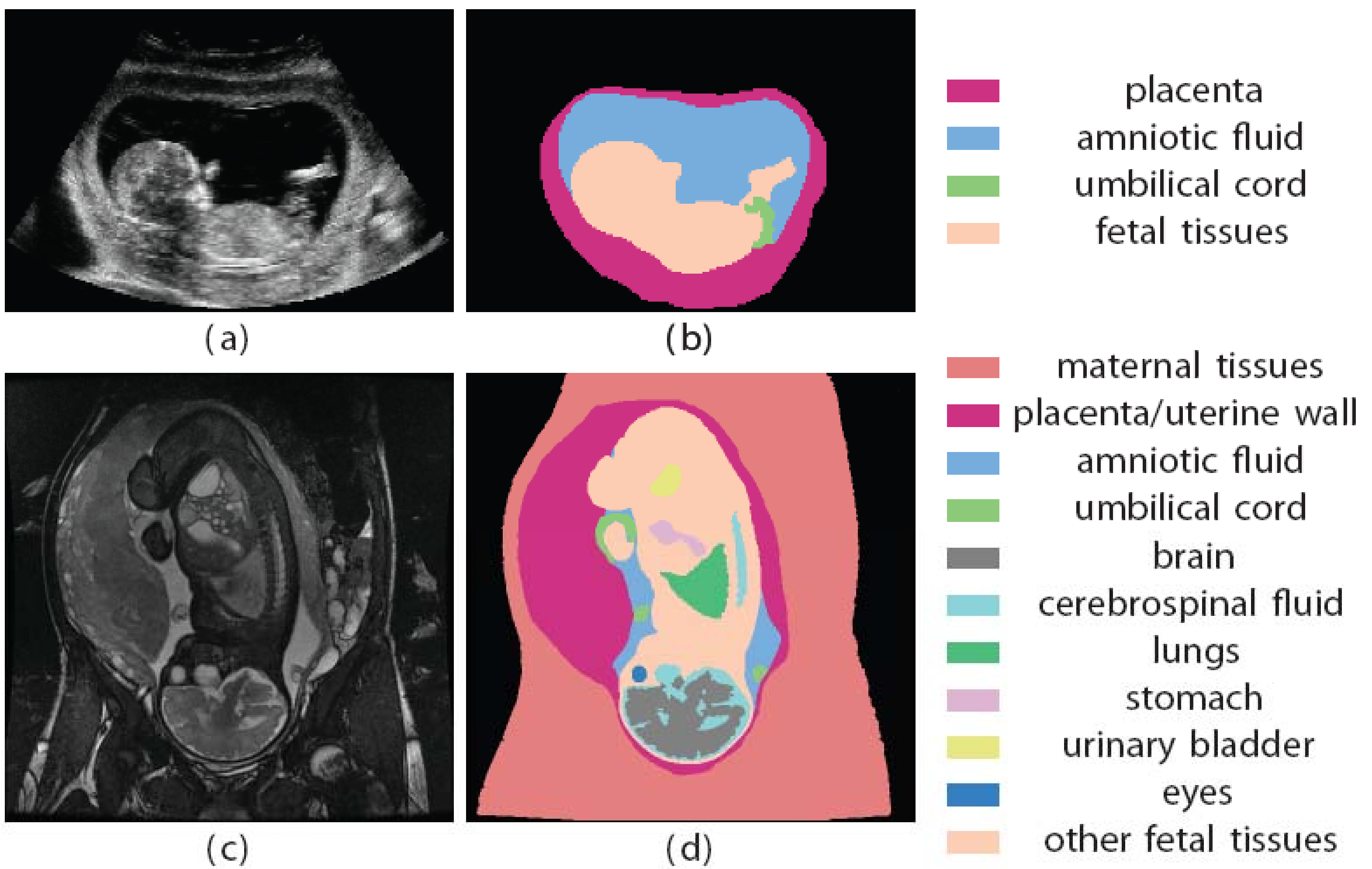
Pregnant Women Models: Tissue labelling

Pregnant Women Models: Surface reconstruction



Pregnant Women Models: Segmentation on MRI

Pregnant Women Models: Tissue labeling



Pregnant Women Models: Smoothing foetus surface

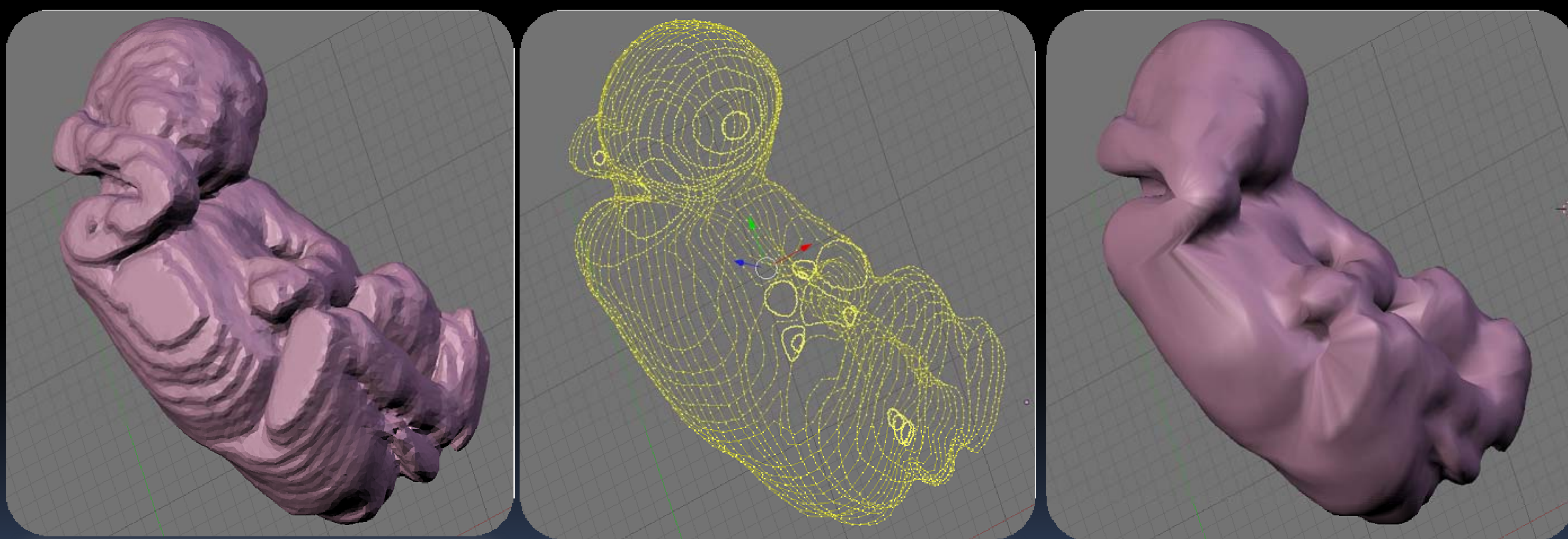
- Anisotropic MRI (1x1x4 mm^3)

  ➡ *staircase* effects.

- Incompatibility with dosimetry studies that require smooth and isotropic objects.

- Gaussian filtering of the segmented objects to reduce this effect.

Pregnant Women Models: Gaussian Filtering of Surfaces

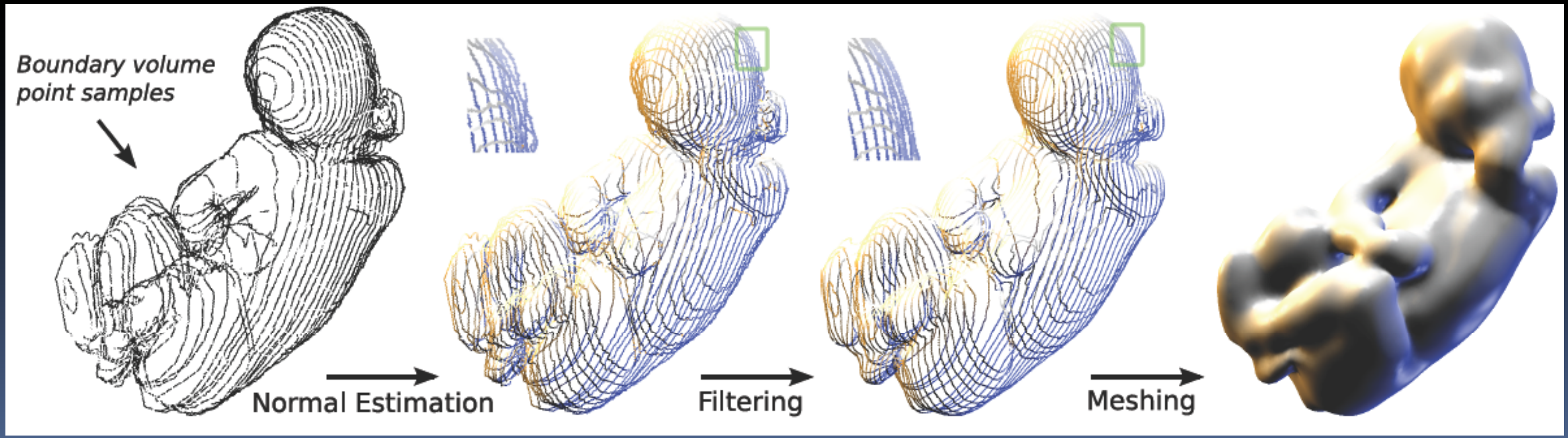


Pregnant Women Models: Point-based surface reconstruction

- Generation of a triangular mesh from a 3D point set
- P: Point set as a surface sampling
  - Position
  - Normal
- Superior surface quality
- Intensively used in computer graphics applications

Pregnant Women Models: Point-based surface reconstruction

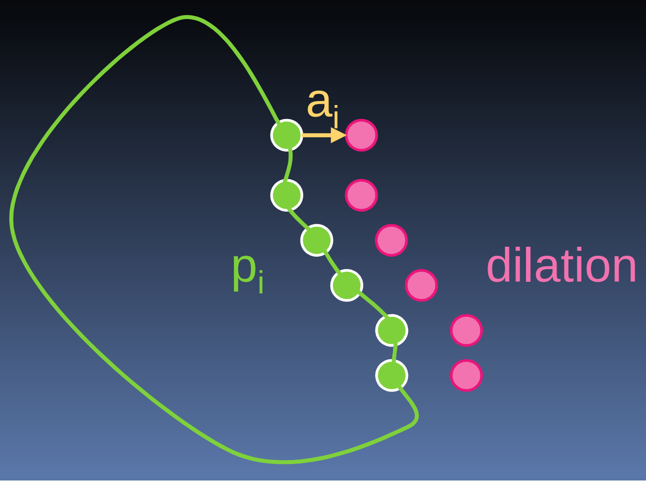
1. Sampling a surface from the segmented volume data, by extracting a set of points.
2. Evaluate normal vectors.
3. Filter the point set, to eliminate:
   1. Small scale high frequency noise.
   2. Outliers.
4. Extract a mesh via contouring



J. Anquez, T. Boubekeur, L. Bibin, E. Angelini and I. Bloch. Utero-fetal unit and pregnant woman modeling using a computer graphics approach for dosimetry studies. MICCAI, London, UK, September 2009.

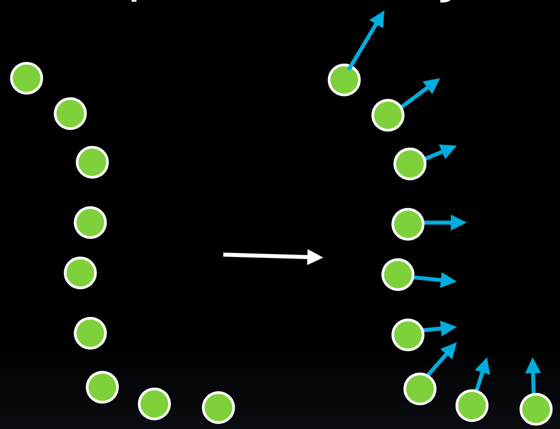
Pregnant Women Models: Point set extraction

- p_i: supervised segmentation.
- a_i: vector associated to p_i to define the exterior orientation (off-constraint).
  - Dilation of the initial segmented object.



Pregnant Women Models: Point Set Normal Evaluation

- **Normal Orientation**: Local *Principle Component Analysis* per point sample [Hoppe 92]
  - Covariance matrix on k-nearest neighbourhoods.
  - Eigen vector associated to the smallest eigen value.



- **Direction**: decided with the off-constraint

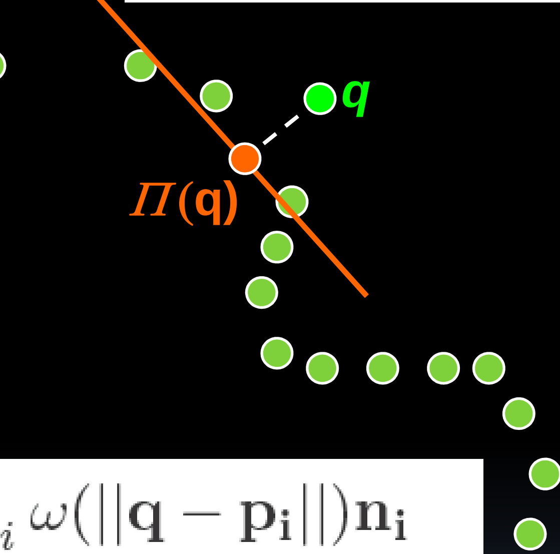
$$\mathbf{n}_i = \frac{\overline{\mathbf{n}_i}}{||\overline{\mathbf{n}_i}||} \quad \text{with} \quad \overline{\mathbf{n}_i} = \begin{cases} \mathbf{u}_i & \text{if} \quad \mathbf{u}_i \cdot \mathbf{a}_i > 0 \\ -\mathbf{u}_i & \text{otherwise} \end{cases}.$$

Pregnant Women Models: Point Set Surface (PSS)

- **Definition**: Smooth surface representation from a point cloud.
- **Operator**: *Moving Least Square* (MLS).
- **Properties**: Approximating or interpolating a set of points to define a continuous surface.
- **Evaluation**:
  - Projection procedure that leads to surface points (stationary points)
  - Implicit form ($f(p)=0$).

Pregnant Women Models: MLS operator

$$H_{\mathbf{q}} = \{c(\mathbf{q}), n(\mathbf{q})\}$$



Projection operator

$$MLS^{\mathcal{P}^N} : \mathbb{R}^3 \rightarrow \mathbb{R}^3, \mathbf{q} \rightarrow \Pi^{\infty}(\mathbf{q})$$

$$\Pi(\mathbf{q}) = \mathbf{q} - < \mathbf{q} - c(\mathbf{q}).n(\mathbf{q}) > n(\mathbf{q})$$

$$\Pi^{i+1}(\mathbf{q}) = \Pi(\Pi^{i}(\mathbf{q}))$$

$$c(\mathbf{q}) = \frac{\sum_i \omega(||\mathbf{q} - \mathbf{p_i}||)\mathbf{p_i}}{\sum_i \omega(||\mathbf{q} - \mathbf{p_i}||)}$$

$$n(\mathbf{q}) = \frac{\sum_i \omega(||\mathbf{q} - \mathbf{p_i}||)\mathbf{n_i}}{||\sum_i \omega(||\mathbf{q} - \mathbf{p_i}||)\mathbf{n_i}||}$$

Wendland’s Quartic kernel

$$\omega(t) = \begin{cases} (1 - \frac{t}{h})^4(\frac{4t}{h} + 1) & \text{if } \; 0 \leq t \leq h \\ 0 & \text{if } \; t > h \end{cases}$$

Pregnant Women Models: Point Set Filtering

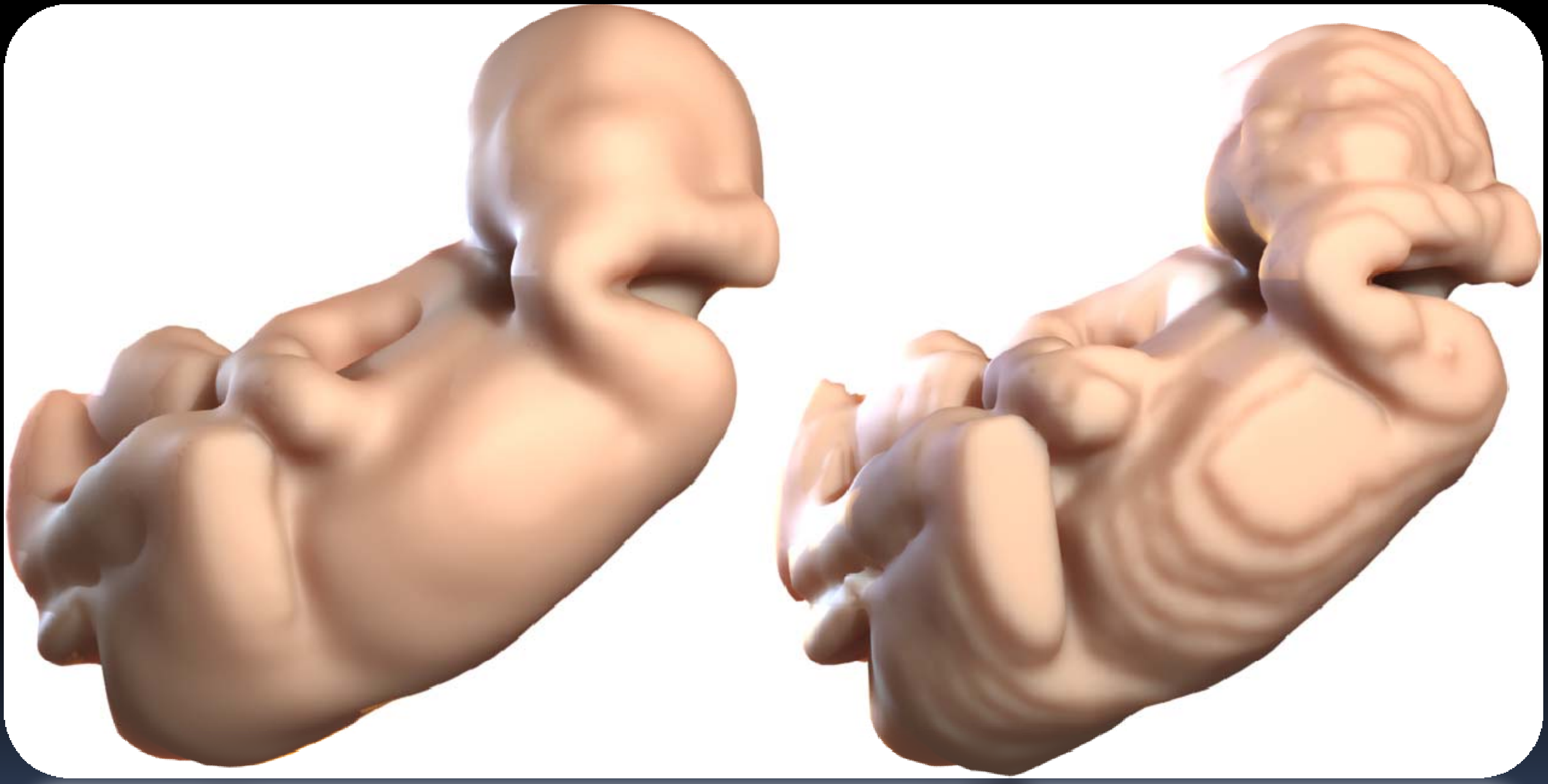
- **Noise removal**: MLS projection directly applied on input samples.
- **Outlier removal**: iterative method based on the Plane Fit Criterion [Weyrich 2003]
  - Criterion based on variance of projection distances on local average plane
  - Iterative outlier search over a quadratic decreasing bound

Pregnant Women Models: Surface meshing

- General case:
  - Implicit PSS
  - Contoured by marching cubes

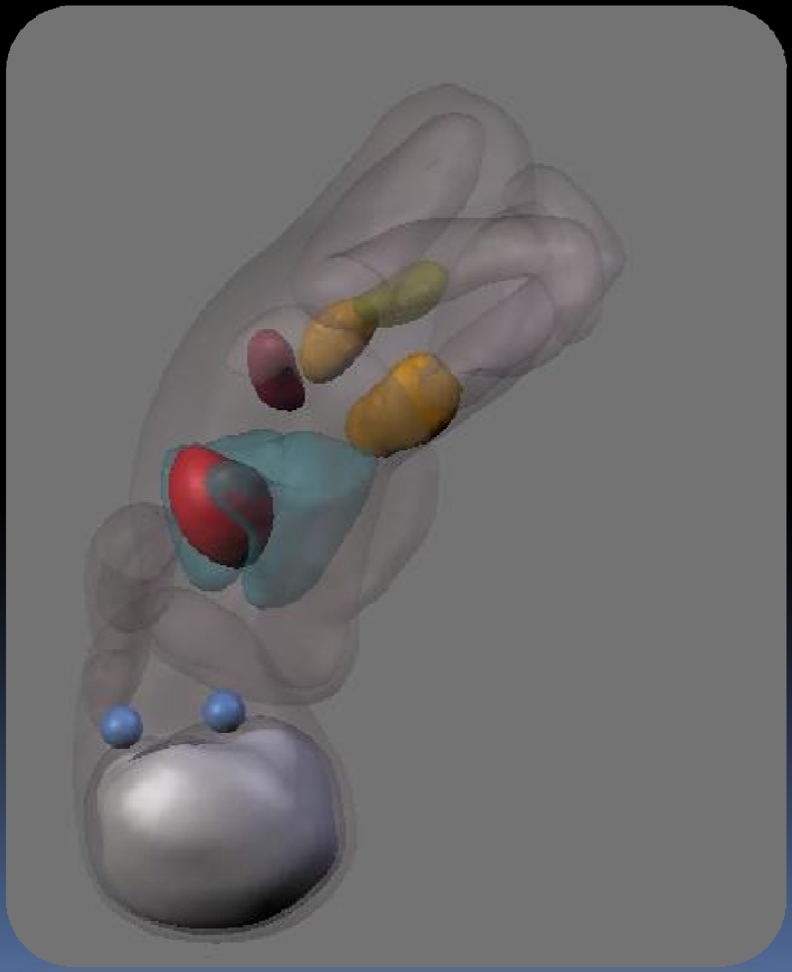
- In case of large missing areas:
  - Poisson Surface Reconstruction [Kazhdan 2006]

Pregnant Women Models: Results



Our reconstruction Direct Meshing

Pregnant Women Models: Foetal organs

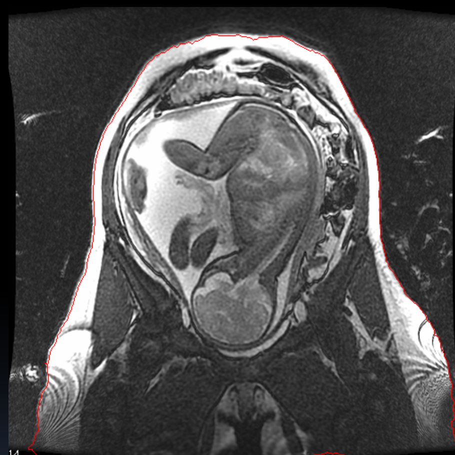


- Brain
- Eyes
- Heart
- Lungs
- Stomach
- Kidneys
- Urinary bladder

Pregnant Women Models: Foetus positioning

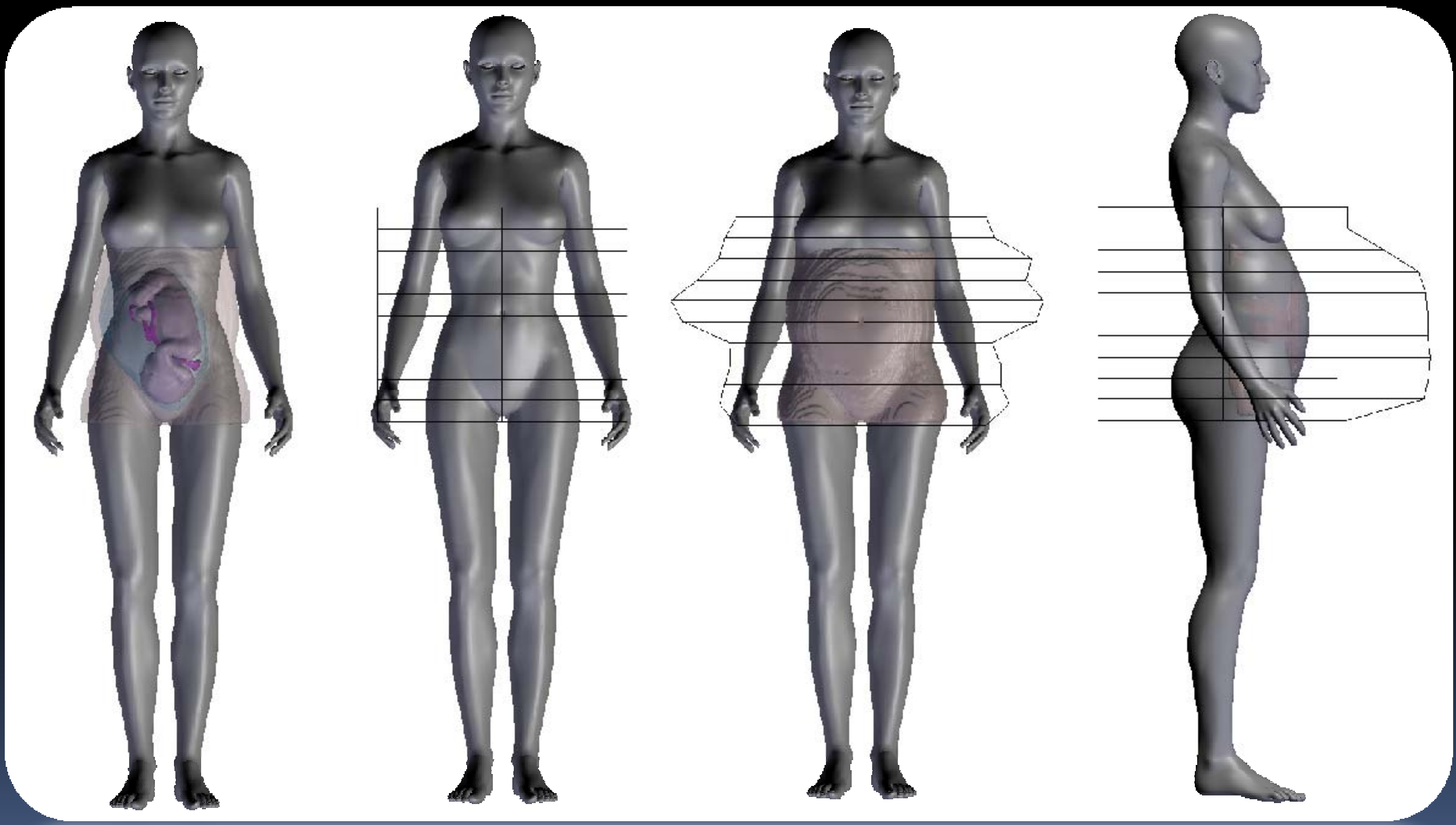
- Only partial information on the mother body

  ➡ synthetic woman model (Daz studio ©)

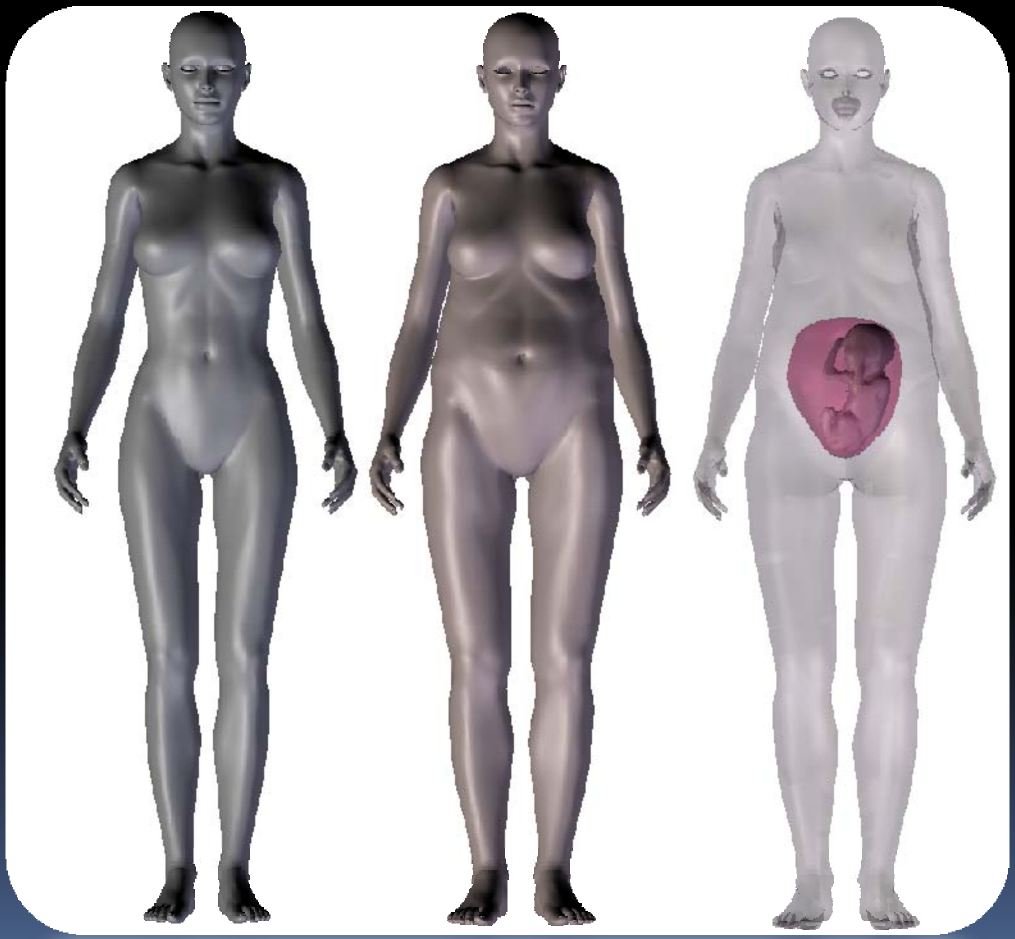


- Deformations to fit the abdominal part partially visible on imaging data (*FFD lattice*).
- Insertion and positioning of the foetus (validated by medical experts).

Pregnant Women Models: Woman body deformations



Pregnant Women Models: Woman body deformations



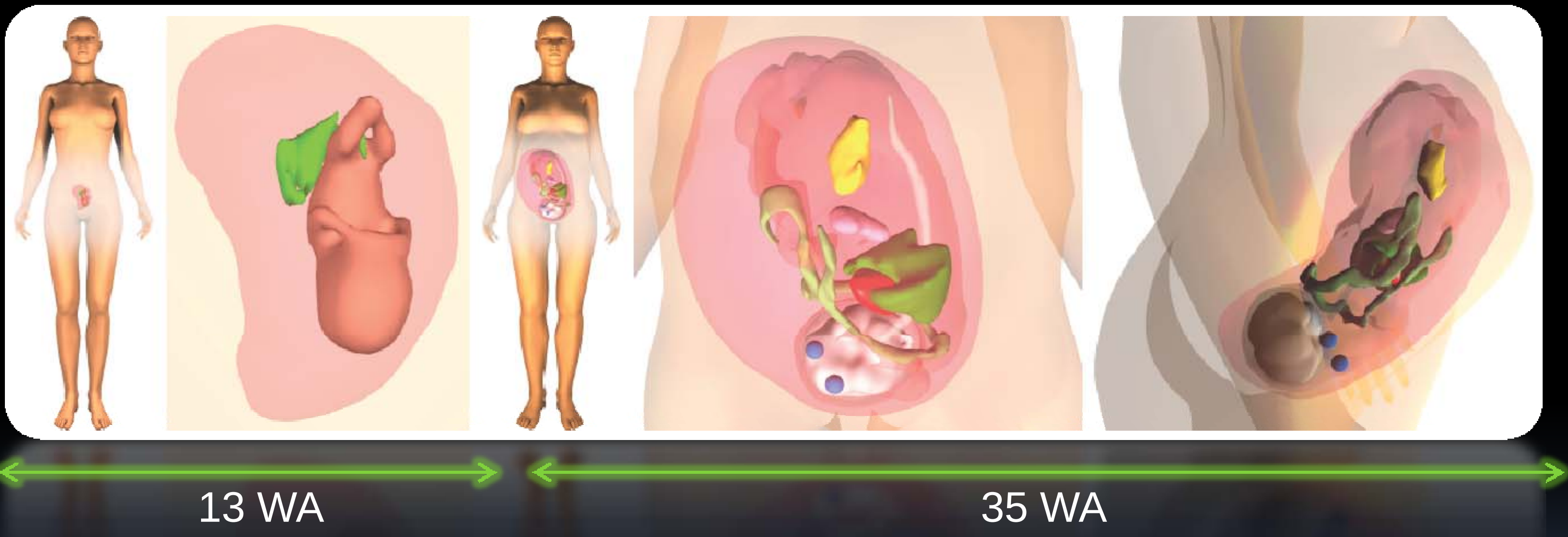
Pregnant Women Models: Foetus positioning

Pregnant Women Models: Set of models

- 4 pregnant women with embryos segmented from US images at 8, 9, 10 and 13 WA.

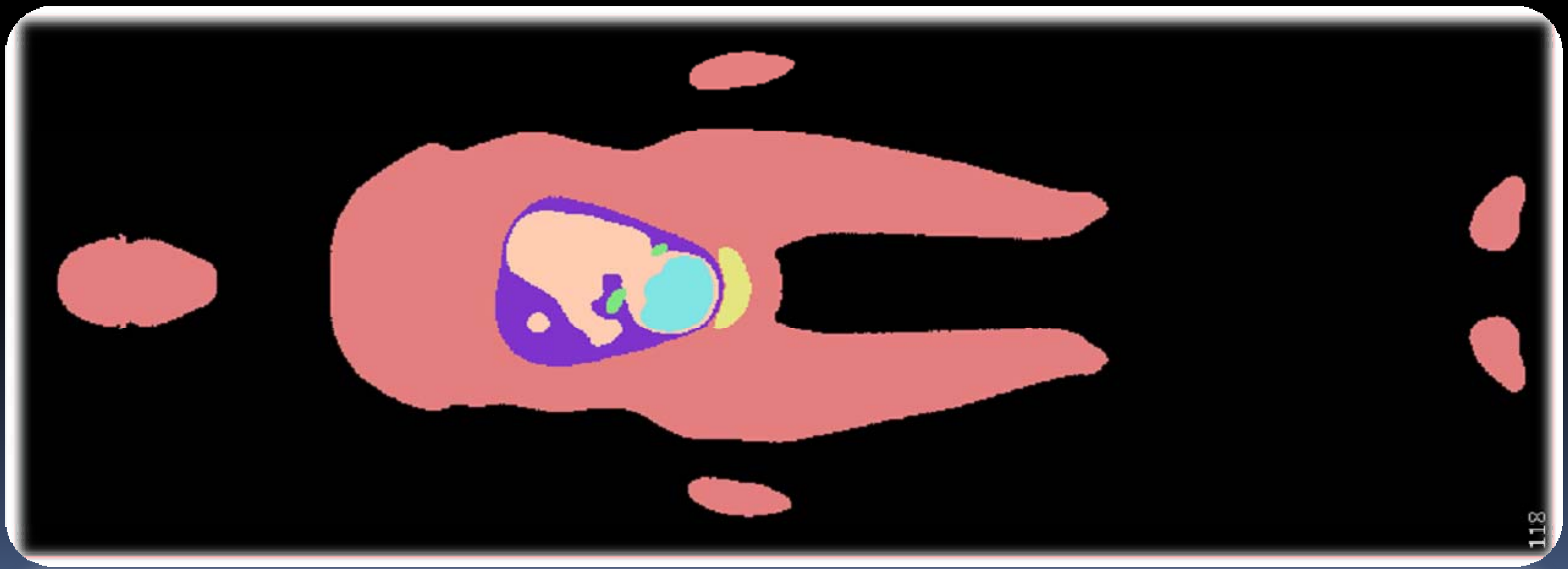
- 5 pregnant women with foetuses segmented from MRI images at 30, 32, 32, 33 and 34 WA (various representative positions).

Pregnant Women Models: Results



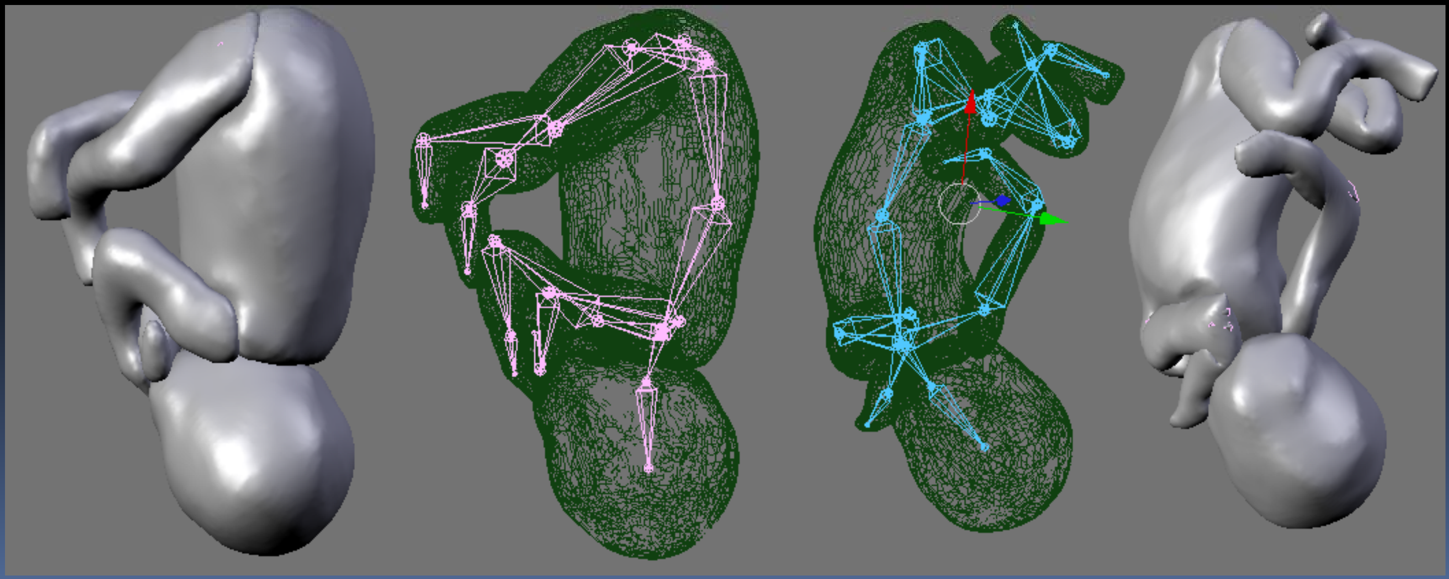
Pregnant Women Models: Voxelized model

- Resolution: 2x2x2 mm^3 .
- One label for each tissue.



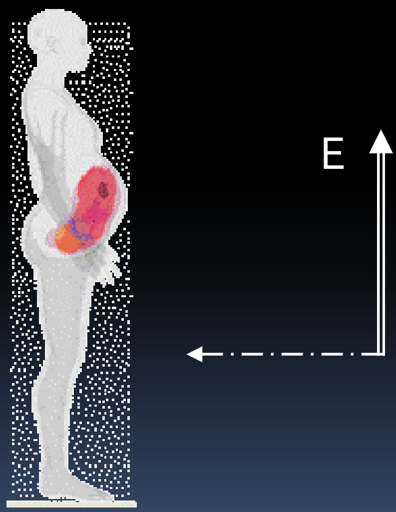
Pregnant Women Models: Armature

- Allow arbitrary foetal positions.
- Unrealistic deformations.
- Automatic foetal segmentation from a generic model.



Dosimetry: Preliminary results

Exposition: Planar frontal wave, Vertical polarization, Frequency: 900 MHz



foetal age (week of amenorrhea)	30	32	32	33	34.5
Whole body SAR ($mW/kg/1W/m^2$) (foetus)	1	1.6	2	1	1.1
Ratio whole body SAR (foetus / pregnant women)	0.16	0.25	0.31	0.18	0.18
Ratio 10 g SAR (foetus / pregnant women)	0.026	0.028	0.042	0.033	0.025
Maximum SAR over 10 g (foetus) mW/kg	5.8	7.8	10.7	8.1	6.2

L. Bibin, J. Anquez, A. Hadjem, E. D. Angelini, J. Wiart and I. Bloch.
Dosimetry studies on a fetus model combining medical image information and synthetic woman body.
11th World Congress on Medical Physics and Biomedical Engineering, Munich, Germany, September 2009.

Dosimetry: other studies

IOP Publishing — Physics in Medicine and Biology
Phys. Med. Biol. 54 (2009) 2755–2767 — doi:10.1088/0031-9155/54/9/011

A comparison of foetal SAR in three sets of pregnant female models

Peter J Dimbylow[1], Tomoaki Nagaoka[2] and X George Xu[3]

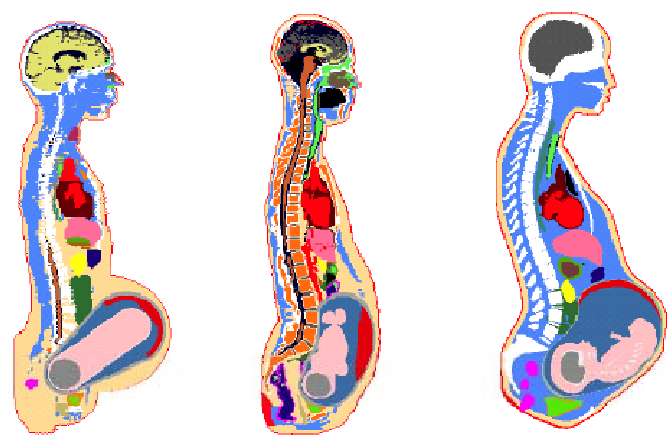


Figure 1. Vertical slices of the HPA, NICT and RPI pregnant models through the mid-axis of the mother at 26-week gestation.

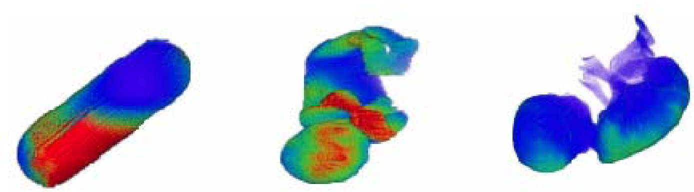


Figure 2. The SAR distribution in 3D volume rendered images of the foetus at 26-week gestation in (from left to right) the HPA, NICT and RPI models at 75 MHz. The colour map is a rainbow spectrum, the highest values in red and the lowest values in violet. The values of the SAR up to 0.1 mW kg^{-1} were linearly spread through the colour map; values above this threshold were set to red. The incident electric field is 1 V m^{-1} (rms), AP for HPA and RPI, and LATr for NICT. The views are from the right side.

Pregnant Women Models: Preliminary dosimetry studies

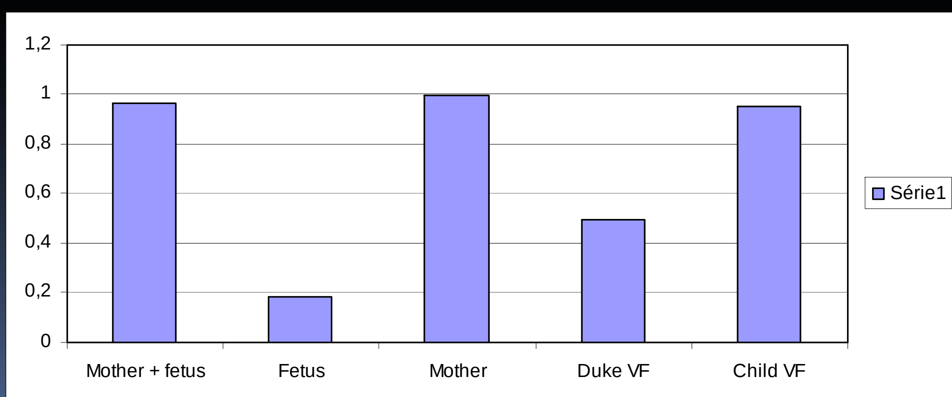
Japanese study

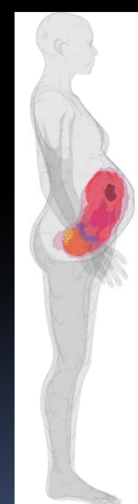
to vertically and horizontally polarized electromagnetic waves from 10 MHz to 2 GHz. We found that pregnancy hardly affected the WBA-SAR, and the average SAR of the fetus of our pregnant-woman model was generally much lower than the WBA-SAR of the mother.

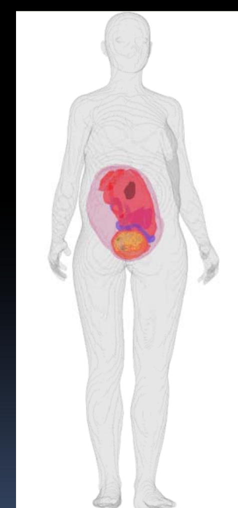
Our preliminary results

@ 900 Mhz with Plane Wave Vertical polarization (

(Adult tissues)







Pregnant Women Models: Preliminary dosimetry studies

SAR vs tissues: Multilayers model

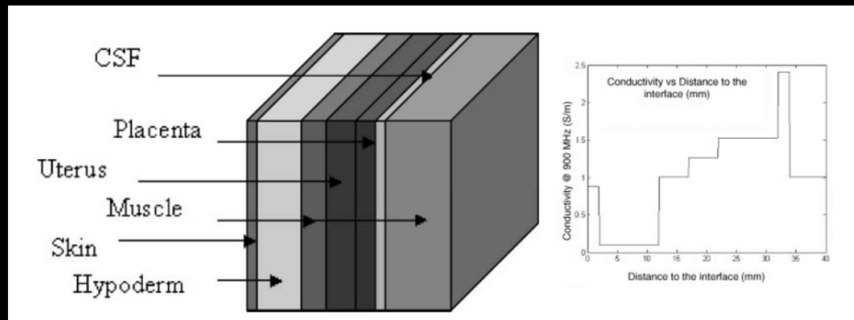
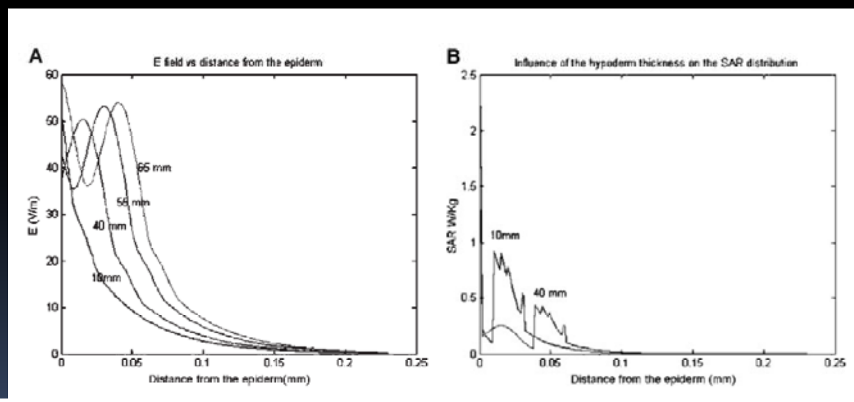


Fig. 19. Planar multiplayer structure (left) and conductivity of the various layers at 900 MHz (right).



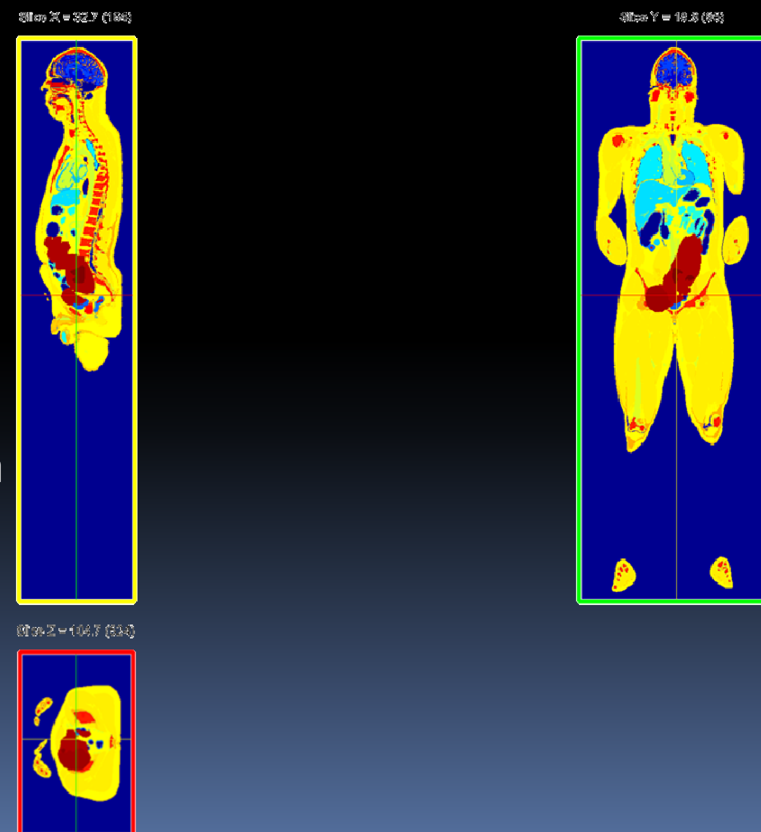
Modeling of RF Head Exposure in Children

J. Wiart,[1]* A. Hadjem,[1] N. Gadi,[1,2] I. Bloch,[2] M.F. Wong,[1] A. Pradier,[1] D. Lautru,[3] V.F. Hanna,[3] and C. Dale[1]

Pregnant Women Models: Preliminary dosimetry studies

Validity of an Homogeneous mother model

- What is the influence of the mother homogenization on the foetus SAR?
- Test models
  - Heterogeneous adult model
  - Homogenization of tissues except a ROI (shape of fetus 34.5 s)
- Test wave
  - Plane wave
  - E=1V/m, F=900MHz



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Model	WBSAR µW/kg VH + Foetus	WBSAR µW/kg Foetus	Ratio WBSAR (VH + foetus)/foetus
VH (heterogeneous) & foetal ROI (heterogeneous)	7.6	2.7	36%
VH (homogeneous) & foetal ROI (heterogeneous)	6.1	0.8	13%
VH (homogenous) & foetus (heterogeneous)	6.2	0.8	13%
VH(skin + homogenous) & foetal ROI(heterogeneous)	6.1	0.8	13%
VH (skin + homogenous) & foetus (heterogeneous)	6.1	0.9	15%
Victoria (homogenous) &foetus (real)	16	3.0	19%
NAOMI (heterogeneous) & foetus (real)	11	4.3	39%

- With a plane wave exposure, the homogenization (of the mother tissues) induces an underestimation of the foetus exposure
- Is it possible to have an equivalent tissues valid for the whole body?
- Is it possible to locally characterize the mother tissues?

Human Body Models: Preliminary dosimetry studies

- Animal studies: variation of the dielectric properties with the age

INSTITUTE OF PHYSICS PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. 46 (2001) 1617–1629 www.iop.org/Journals/pb PII: S0031-9155(01)21688-1

Changes in the dielectric properties of rat tissue as a function of age at microwave frequencies

A Peyman[1], A A Rezazadeh[1] and C Gabriel[2]

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Phys. Med. Biol. 52 (2007) 2229–2245 doi:10.1088/0031-9155/52/8/013

Dielectric properties of porcine cerebrospinal tissues at microwave frequencies: *in vivo*, *in vitro* and systematic variation with age

A Peyman[1], S J Holden[2], S Watts[2], R Perrott[2] and C Gabriel[1]

Pregnant Women Models: Preliminary dosimetry studies

Exposure induced by a handset:

In foetus,

900 MHz

SAR = 0.02 W/kg.

SAR max10g Sphere = 0.71 W/kg
SAR max10g Cube = 0.58 W/kg

Question: what is the validity of tissue homogenization?

Conclusions

- We have developed models of pregnant women with detailed utero-foetal units:
  - at different periods of the gestation,
  - in different positions,
  - validated by medical experts !
- Dosimetry simulations of SAR measurements show that:
  - Global and local exposures of the foetus are much lower than for the mother.
  - Foetal exposure depends of the foetal position!

Thank you for your attention.

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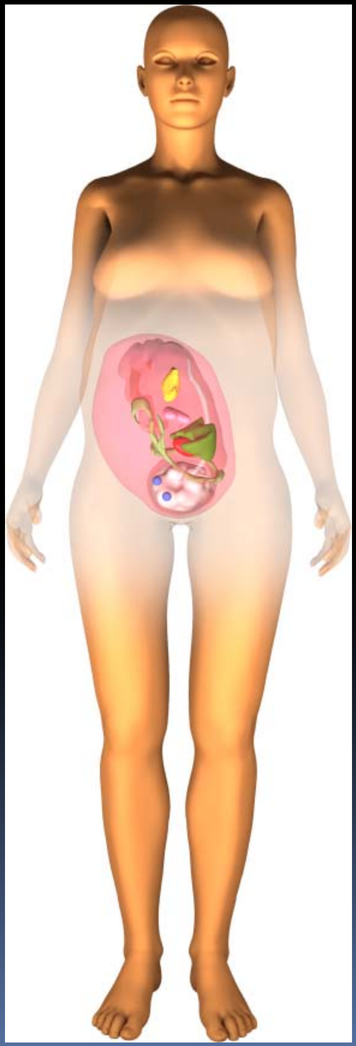
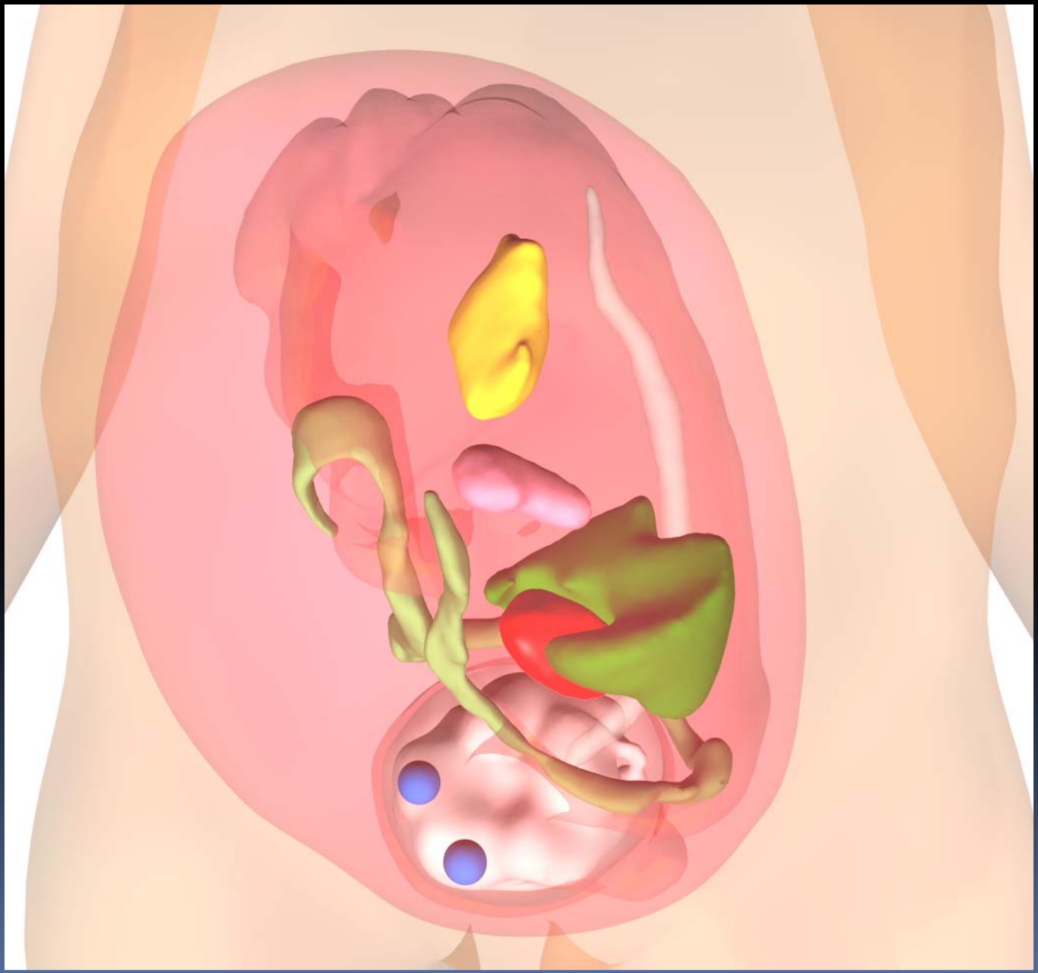
- Les propriétés diélectriques des tissus sont consultables sur le lien de la Federal Communication Commission:

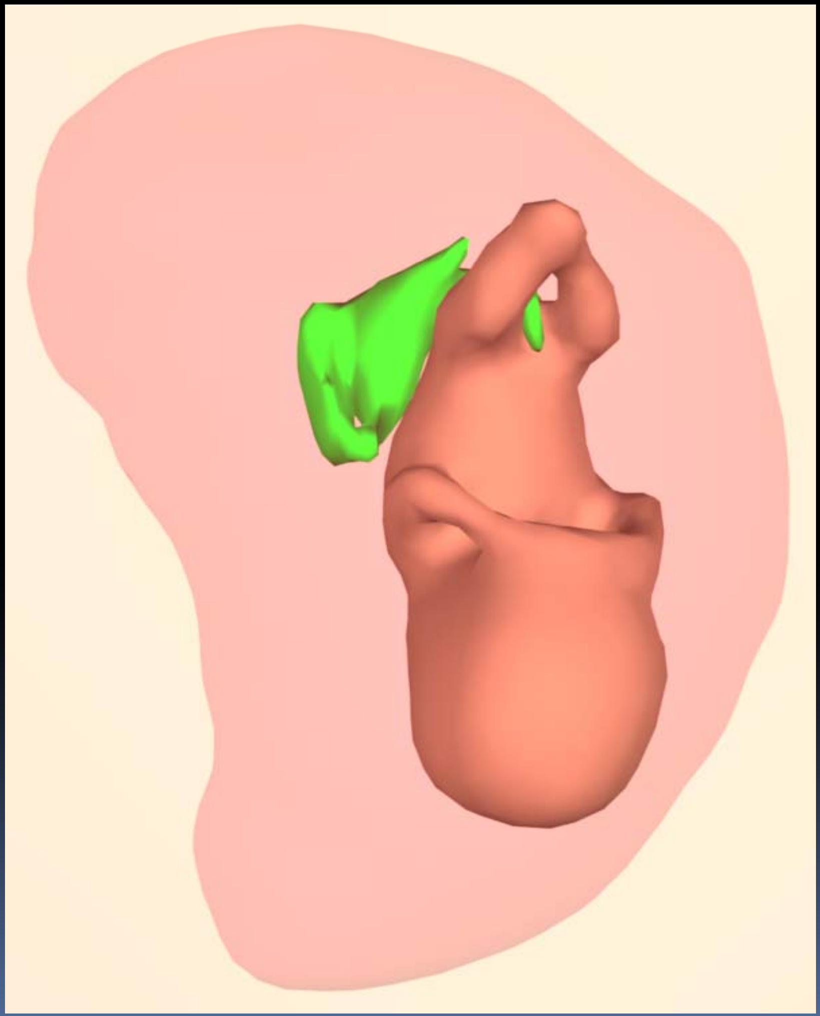
  http://www.fcc.gov/fcc-bin/dielec.sh

Models





Models



Finite Difference in Time Domain(FDTD)

- The Maxwell Partial Differential equations are estimated via finite differences
- The tissues are modelled with voxels