FEM/XFEM-Based Modeling of Brain Shift, Resection, and Retraction for Image-Guided Surgery

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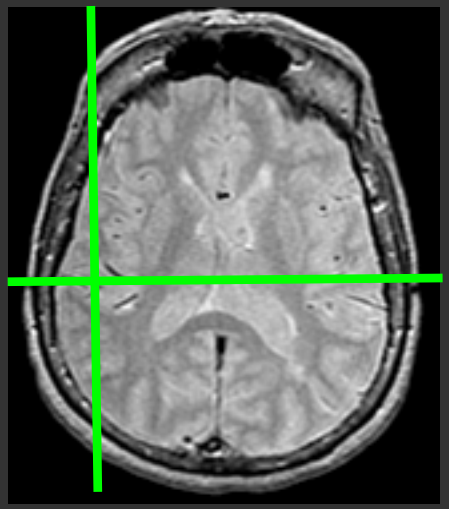
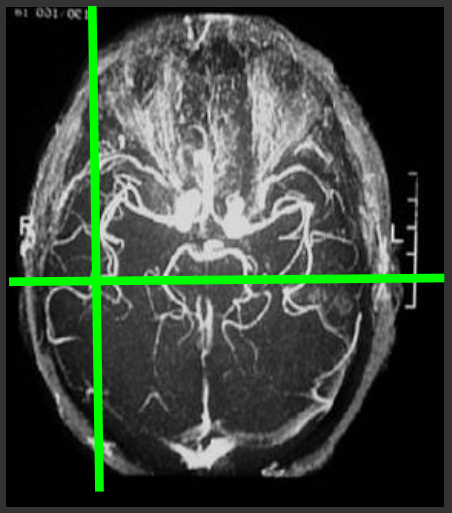
Image-Guided NeuroSurgery (IGNS) systems

Before surgery, IGNS systems bring preoperative images into correspondence

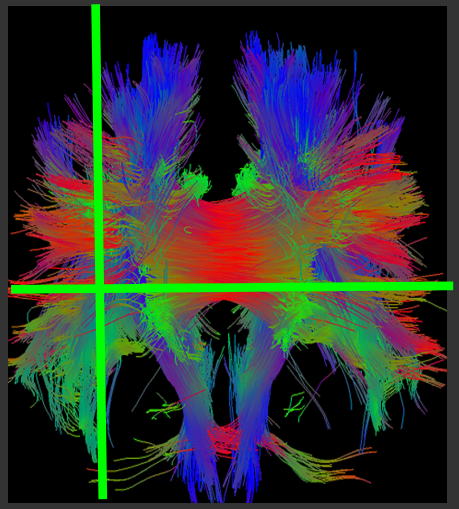
CT



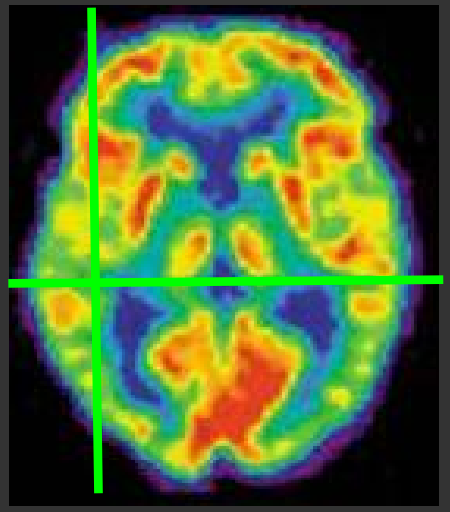
MRI



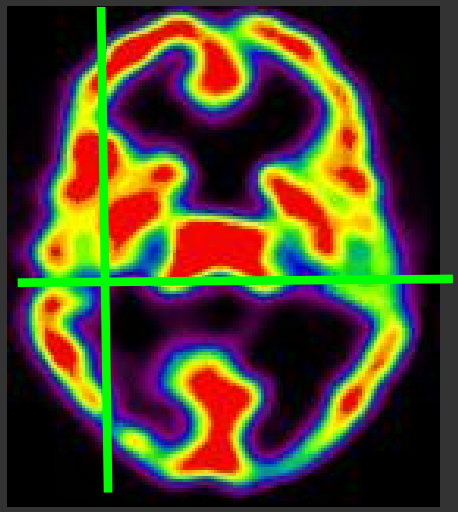
Angiography



DTI

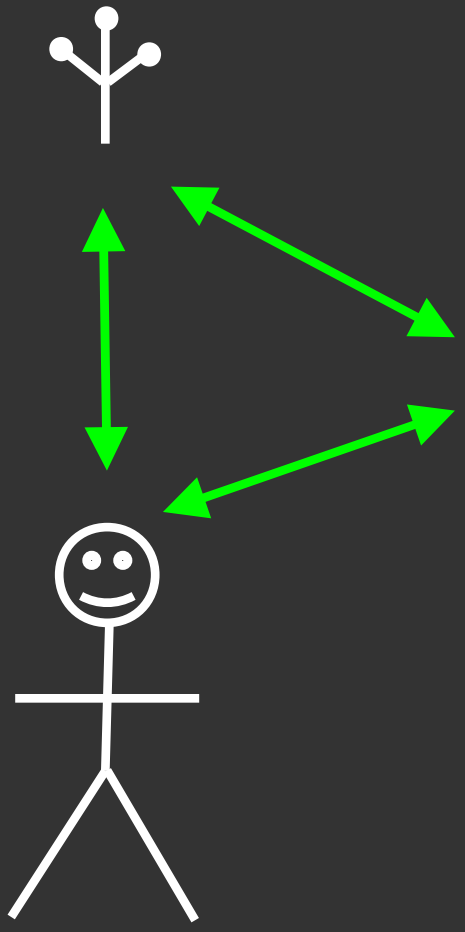


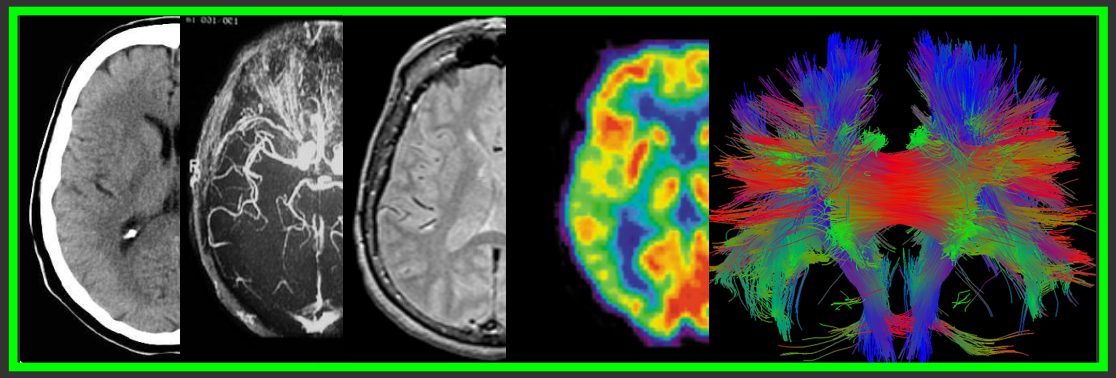
PET



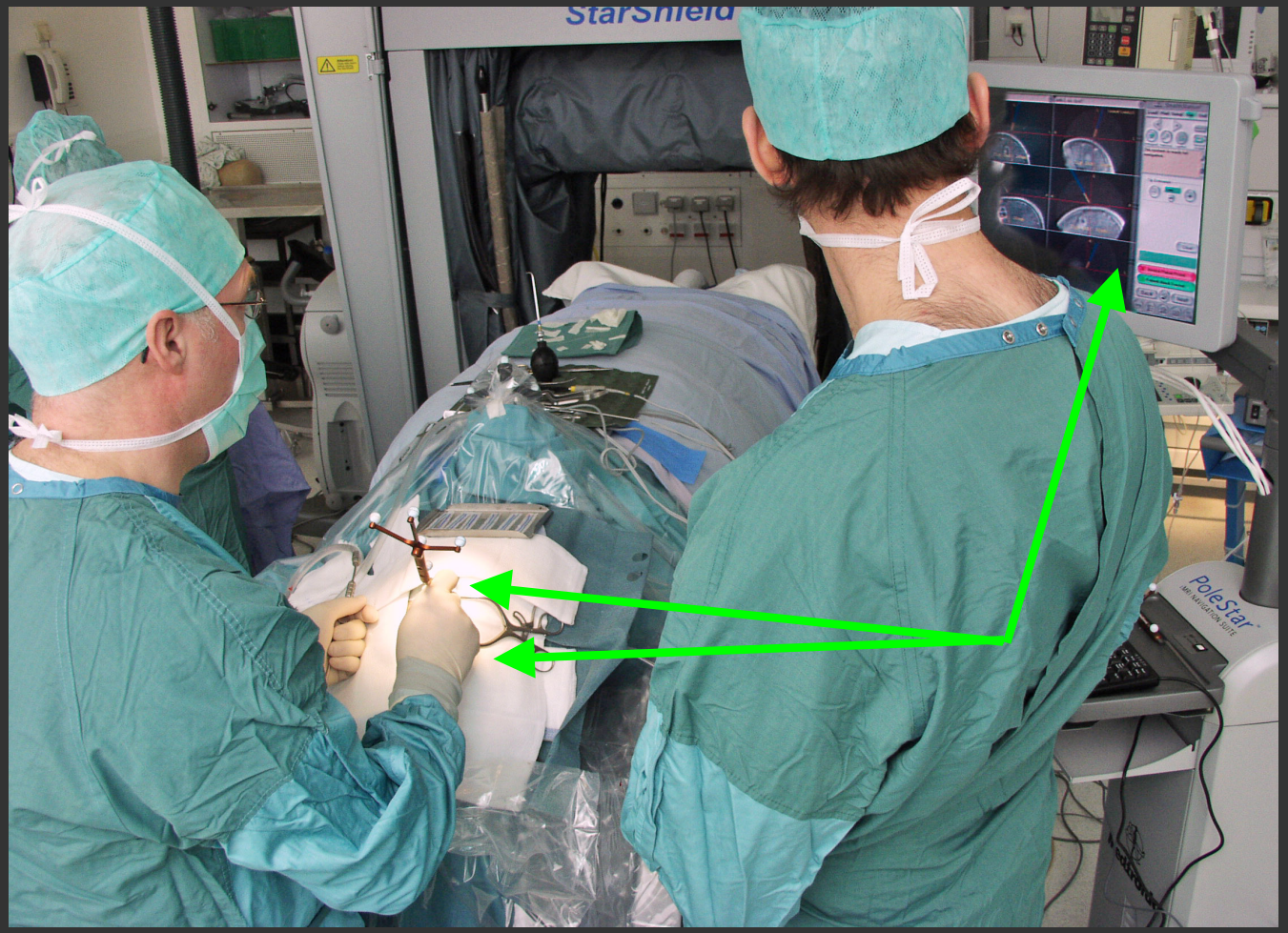
SPECT

During surgery, IGNS systems brings preoperative images, patient's brain, and probe into correspondence





IGNS systems allow simultaneous navigation in brain and preoperative images

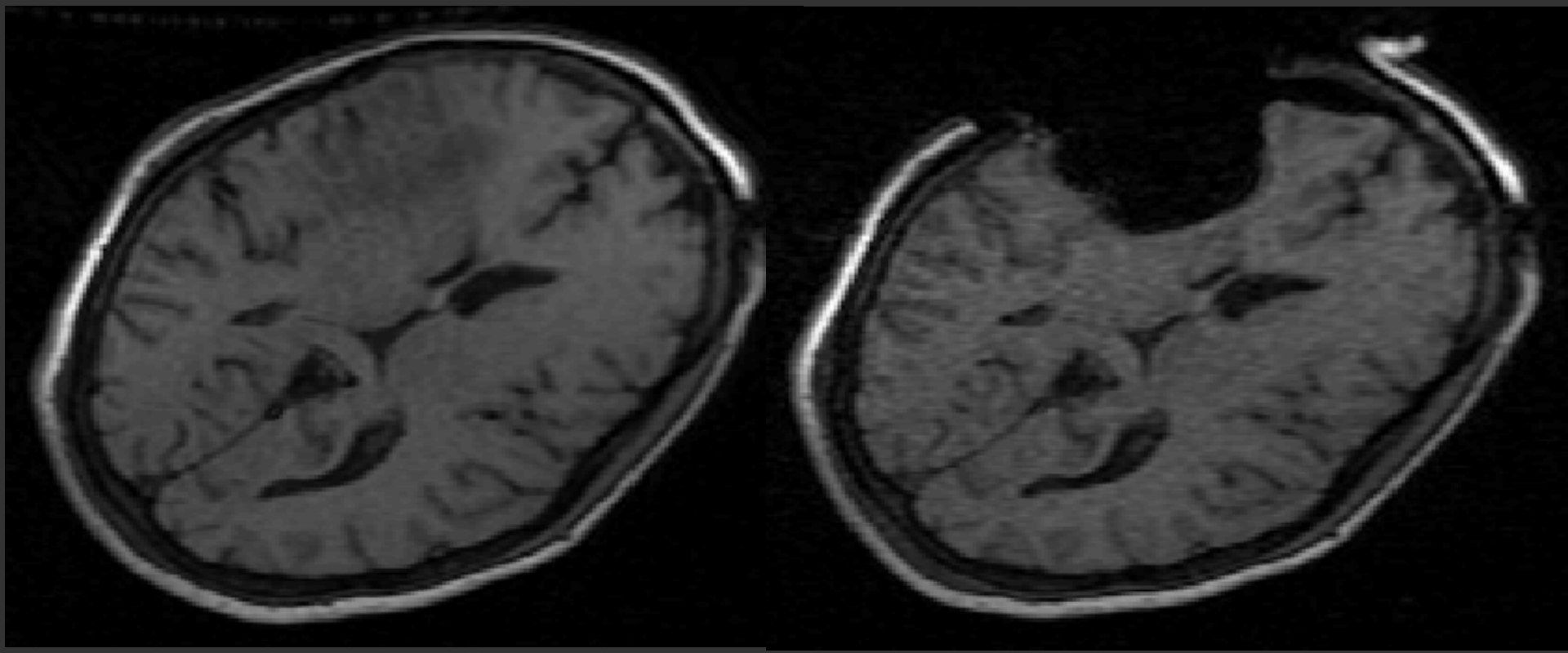


(University Hospital (CHU), Liège, Belgium)

Accuracy ~mm (Hastreiter et al., 2004)

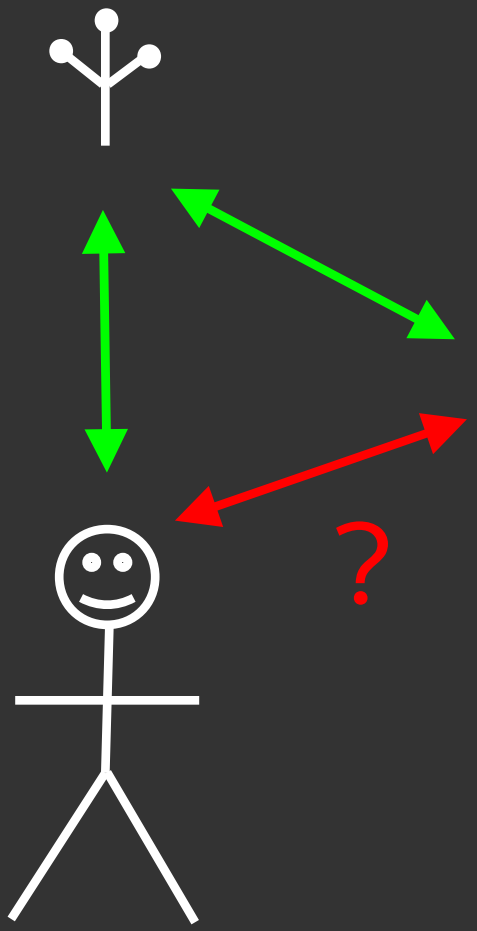
Major limitation of IGNS systems: brain deforms during surgery (1) Shift

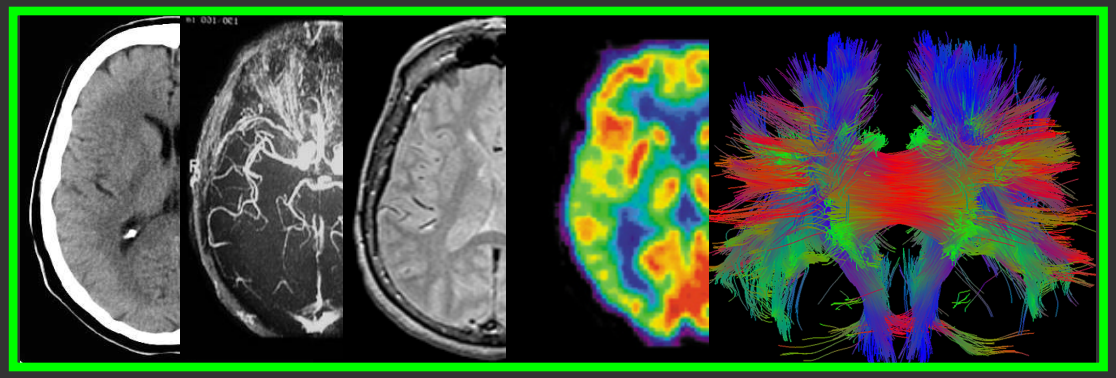
Major limitation of IGNS systems: brain deforms during surgery (2) Resection



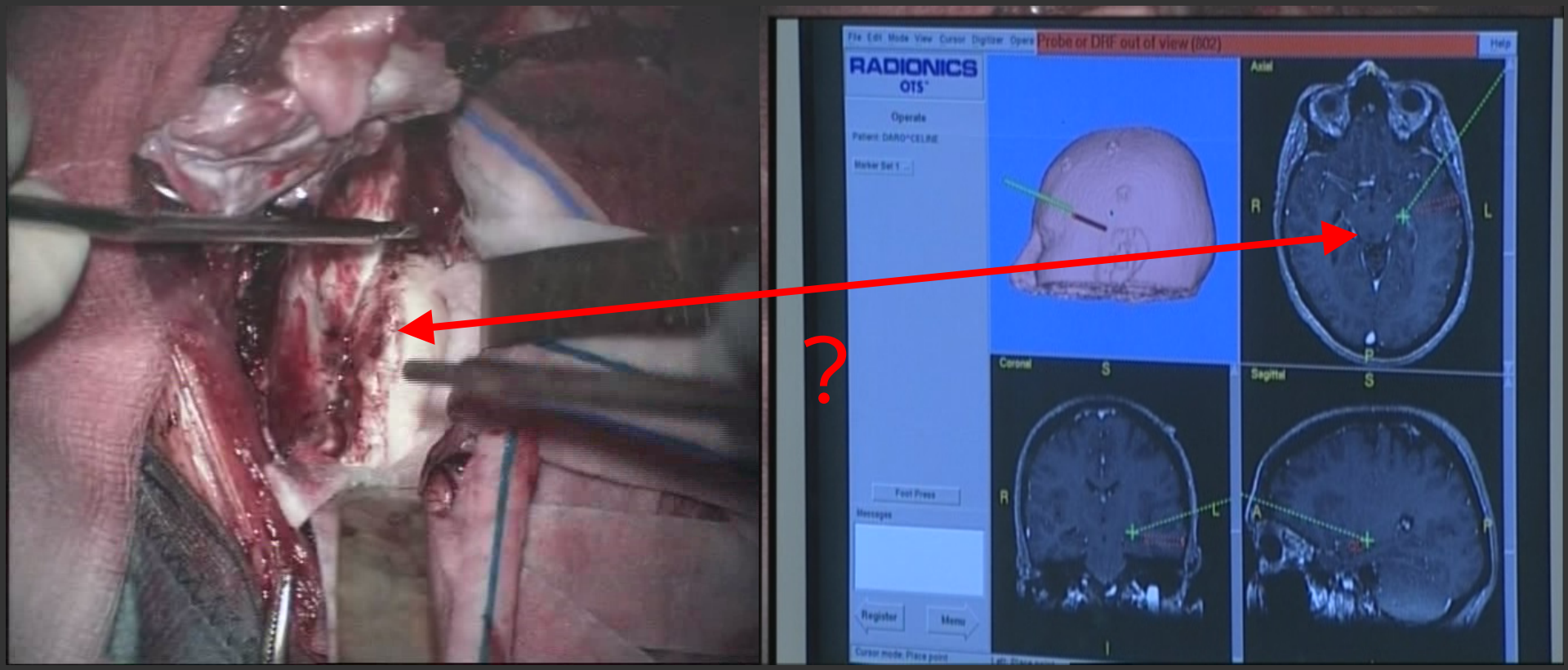
Major limitation of IGNS systems: brain deforms during surgery (3) Retraction

During surgery, IGNS systems loose correspondence between preoperative images and intraoperative brain configuration



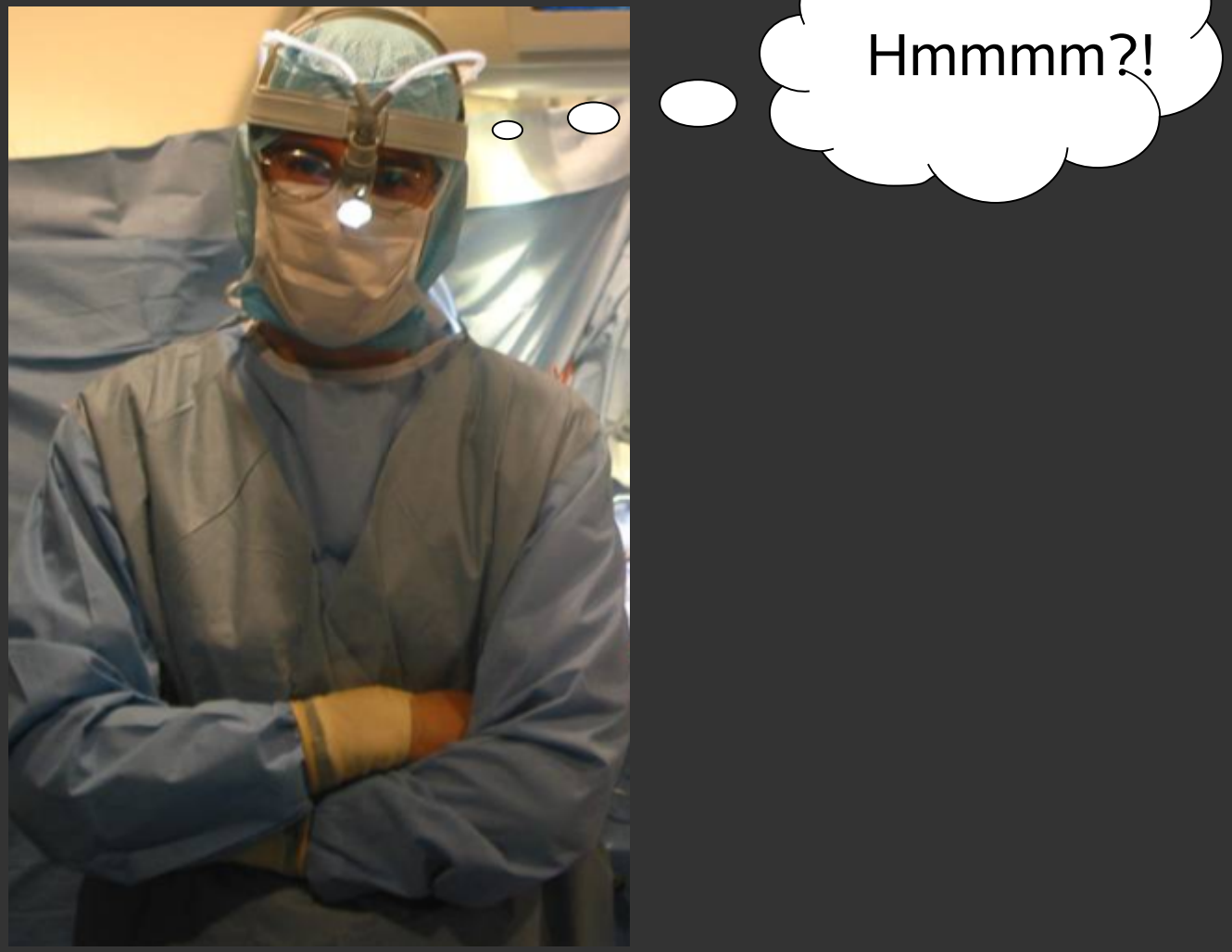


During surgery, accuracy of IGNS systems decreases



Accuracy ~~~mm~~ → Accuracy ~cm (Hastreiter et al., 2004)

A first solution is to mentally compensate for intraoperative deformations



A second solution is to acquire intraoperative images (1)

High-field (0.5 T) intraoperative MRI scanner

General Electric, Signa SP

As installed at Brigham & Women's Hospital, Harvard University, Boston, USA

A second solution is to acquire intraoperative images (2)

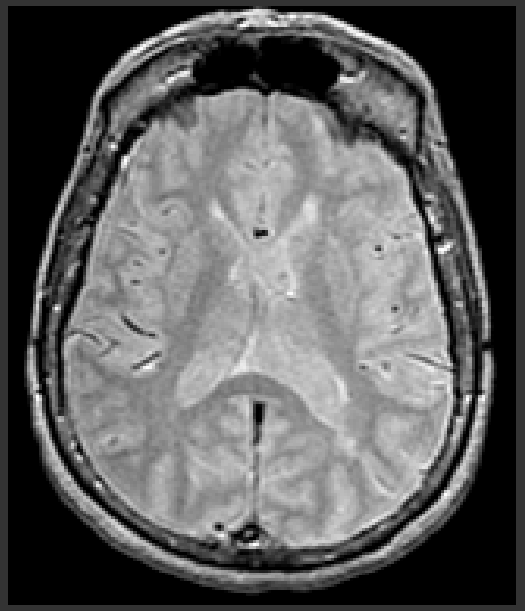
Low-field (0.2 T) intraoperative MRI scanner

Odin (Medtronic), PoleStar N20

Available, e.g. at University Hospital (CHU), University of Liège and Erasme Hospital,Univ. of Brussels, Belgium

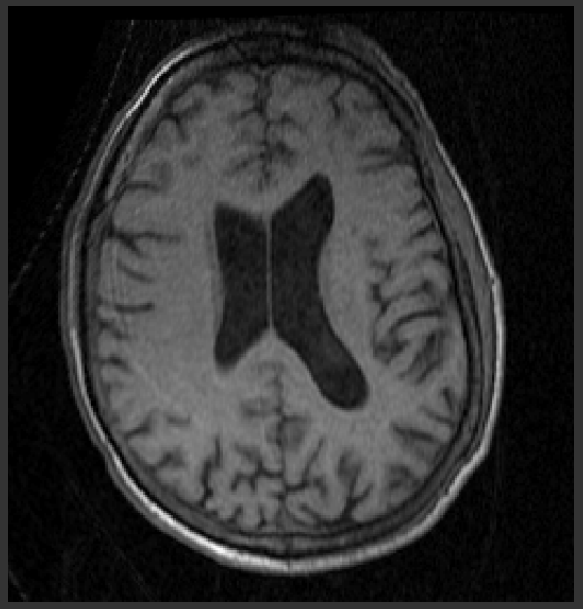
Issues (1): intraoperative MR images are generally of lower quality

Preoperative MR



1.5 Tesla
for reference

Intraoperative MR

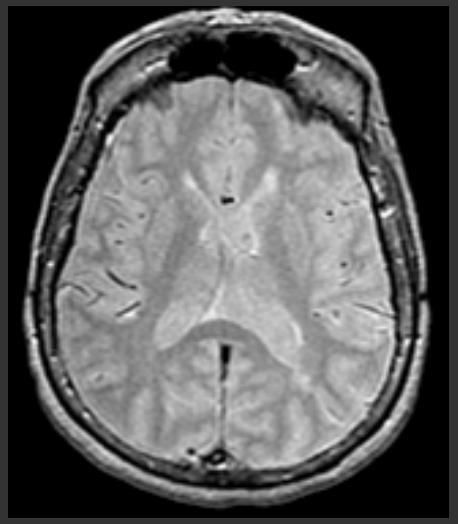


High-field
0.5 Tesla

Low-field
0.2 Tesla

Issues (2): Only a few intraoperative modalities are available and can be acquired in real-time

So far:

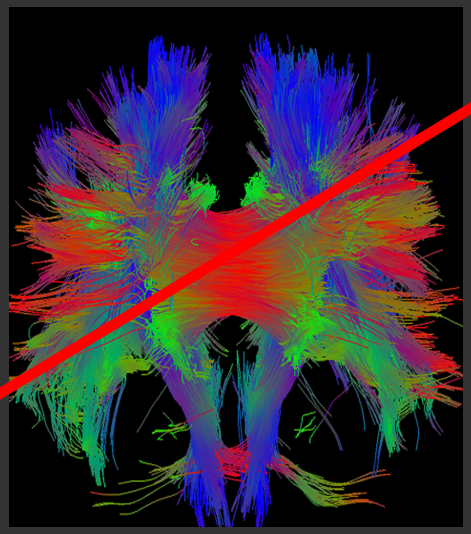


MRI

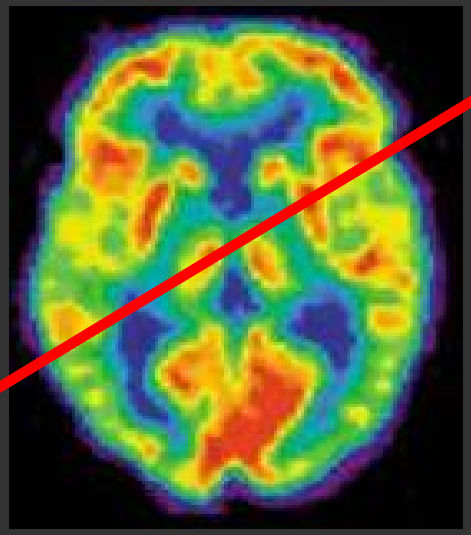
CT

Ultrasound

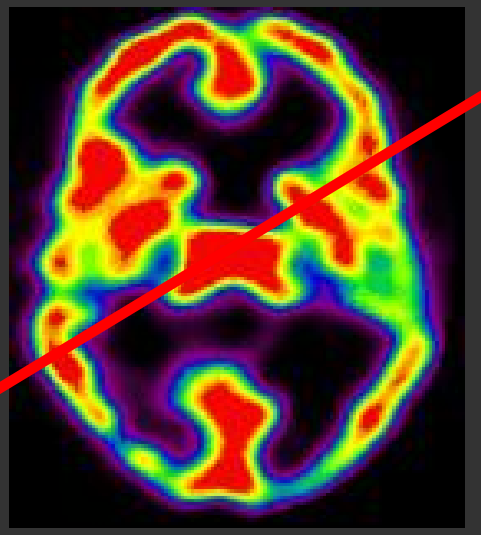
...



DTI



PET



SPECT

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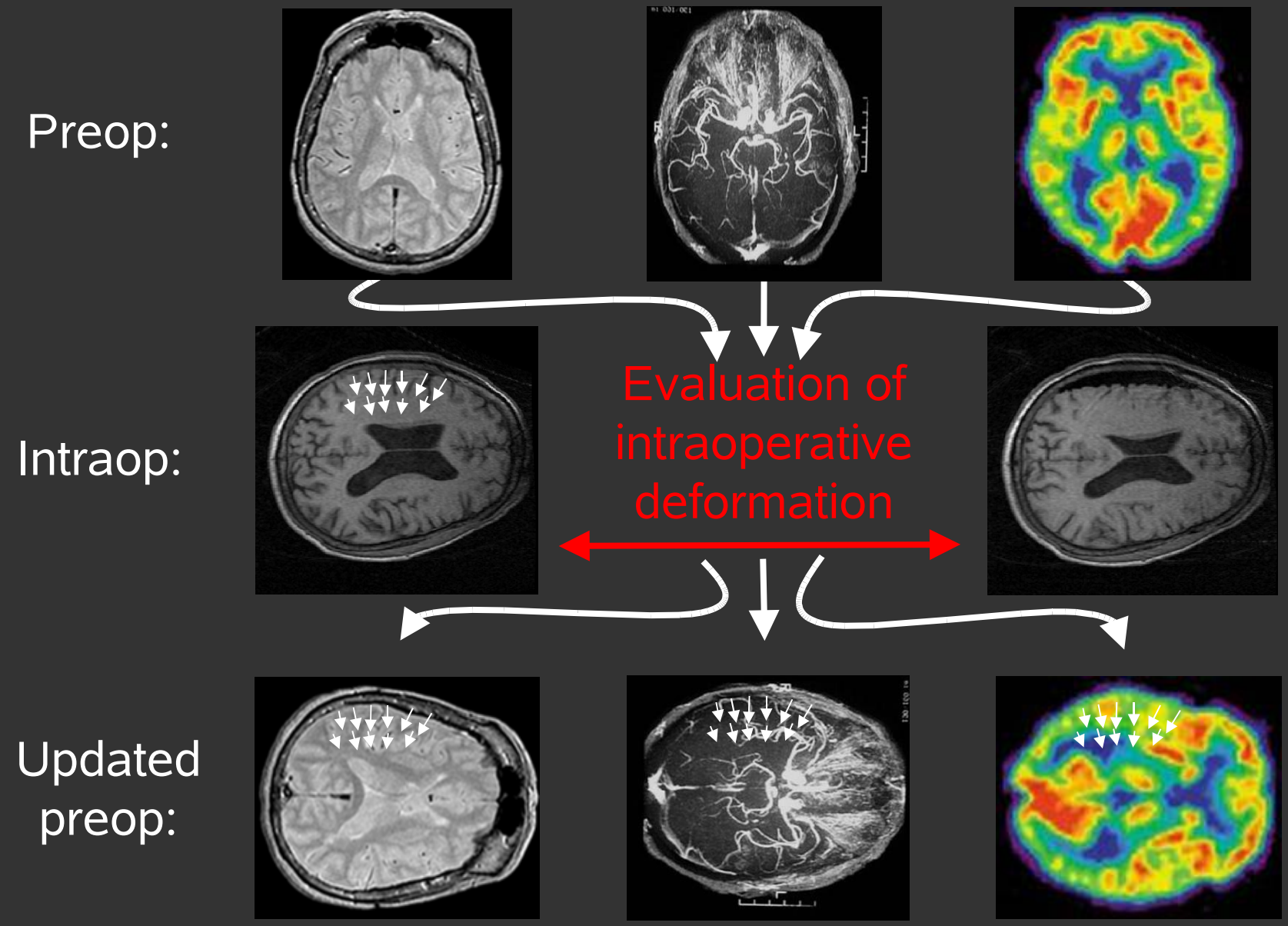
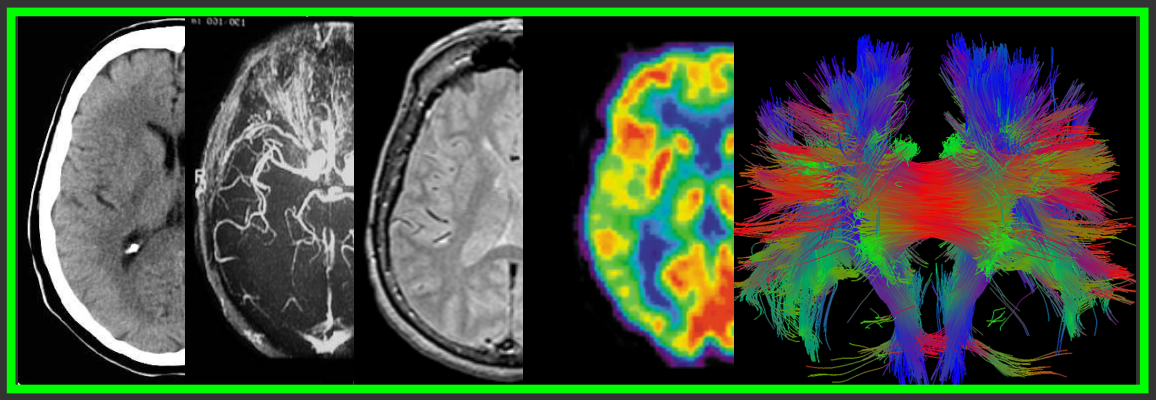
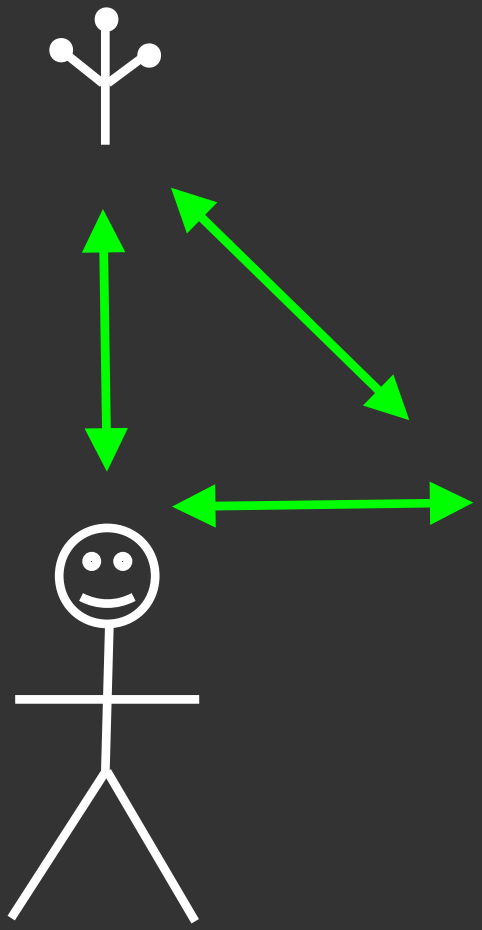
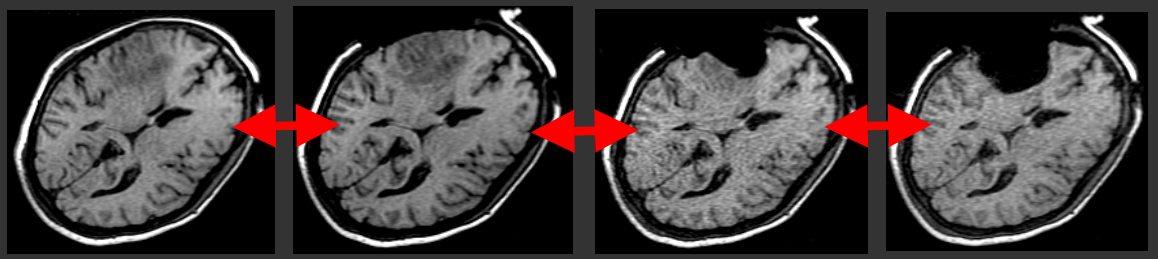
How to bring the most information together ?



The update of preoperative images is the current limit of IGNS systems

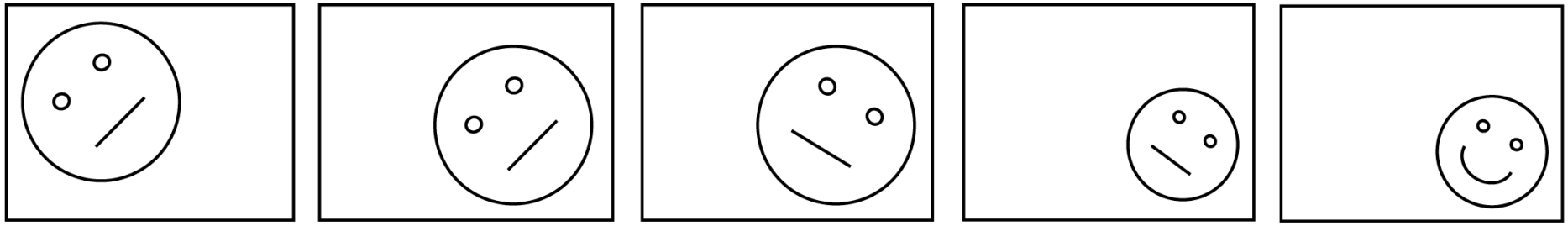




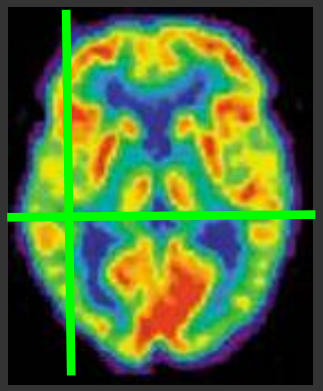


Successive intraoperative MR (iMR) images

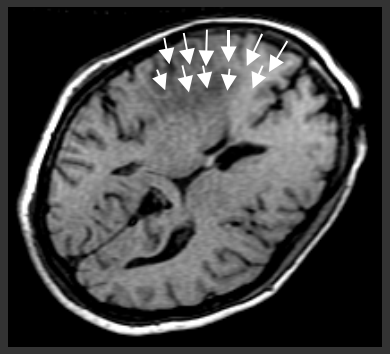
Present and future of IGNS systems

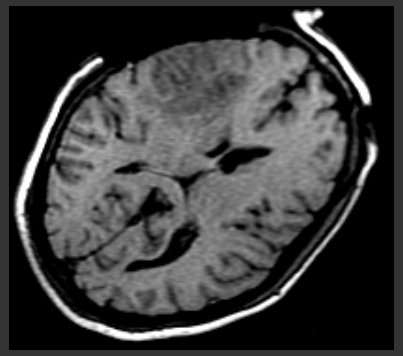


Rigid

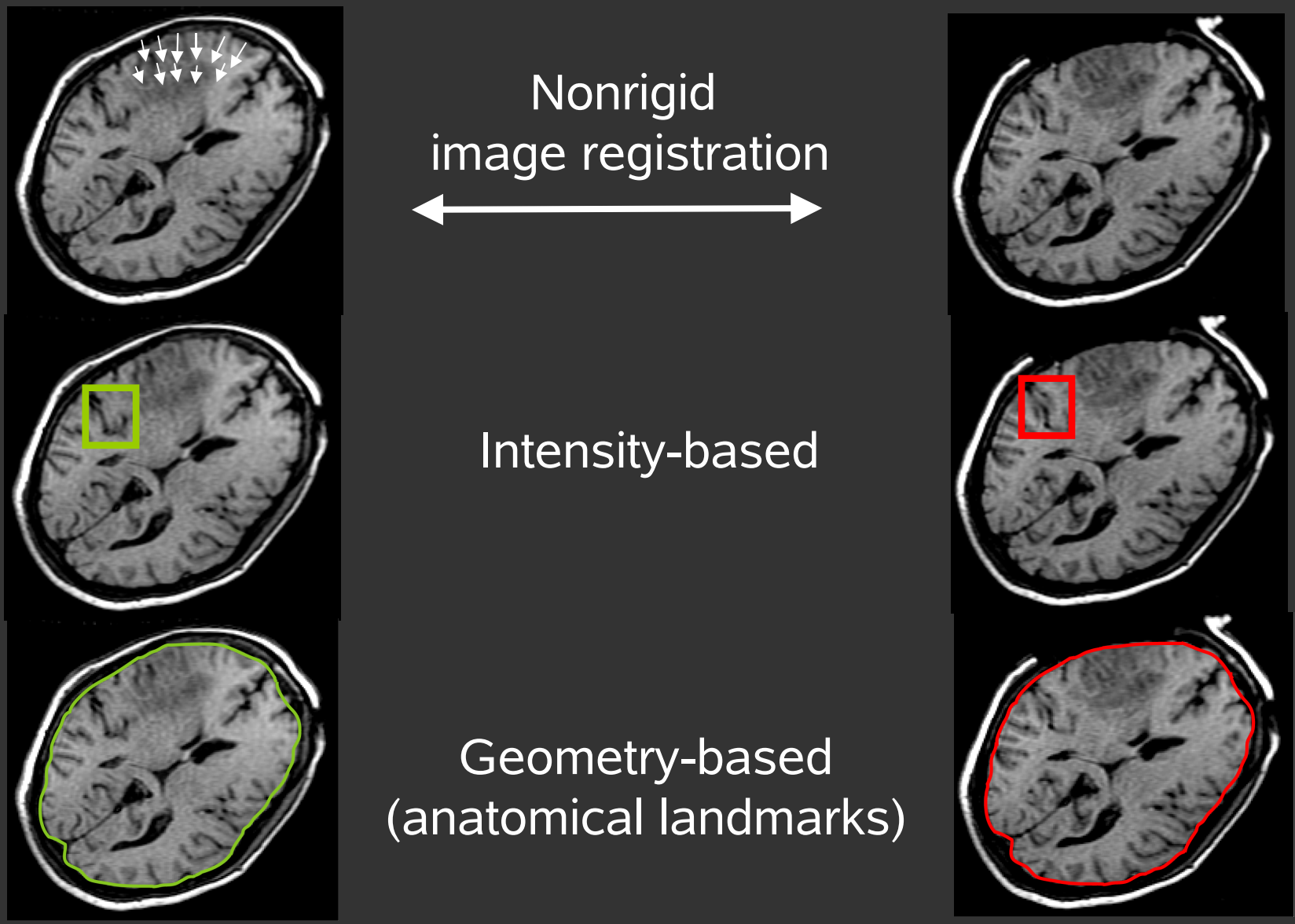


Nonrigid



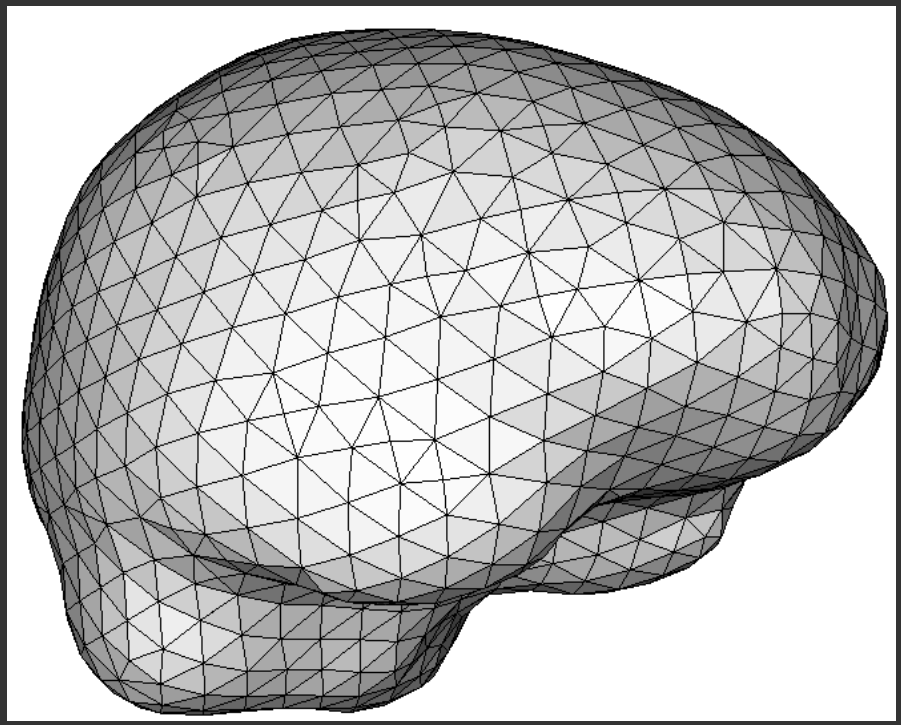


Similarity measure for nonrigid registration



Transformation for nonrigid registration

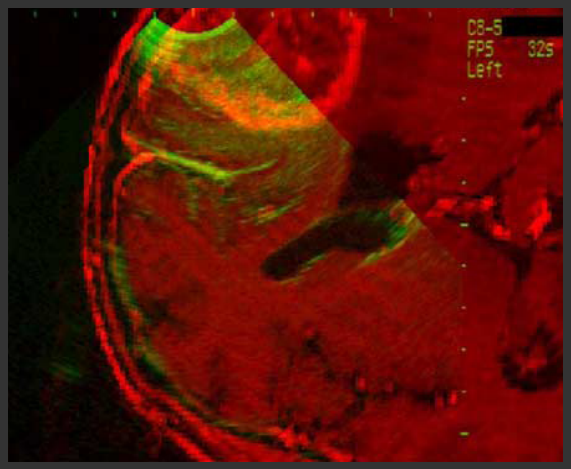
B-splines



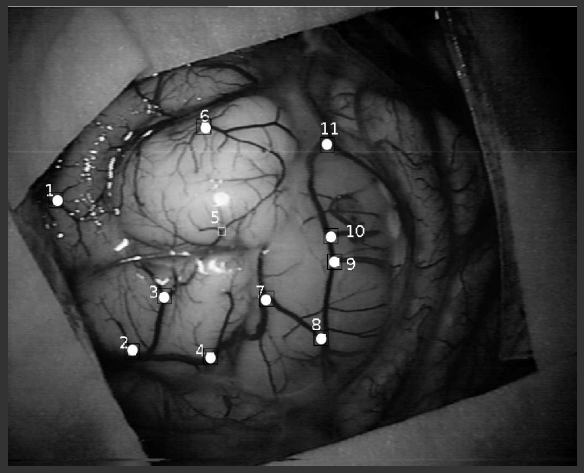
Biomechanical models

State-of-the-art

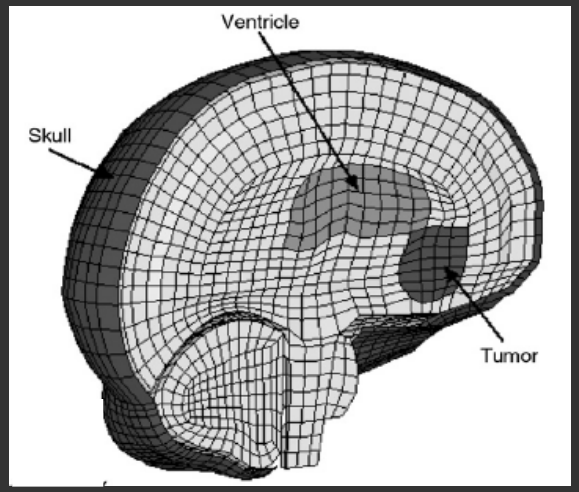
Large majority of research on one deformation, generally brain shift



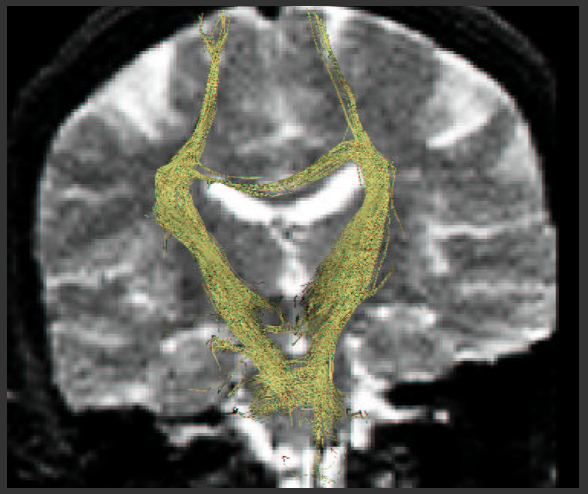
Lunn, Paulsen, et al.



Paul, Jannin, et al.



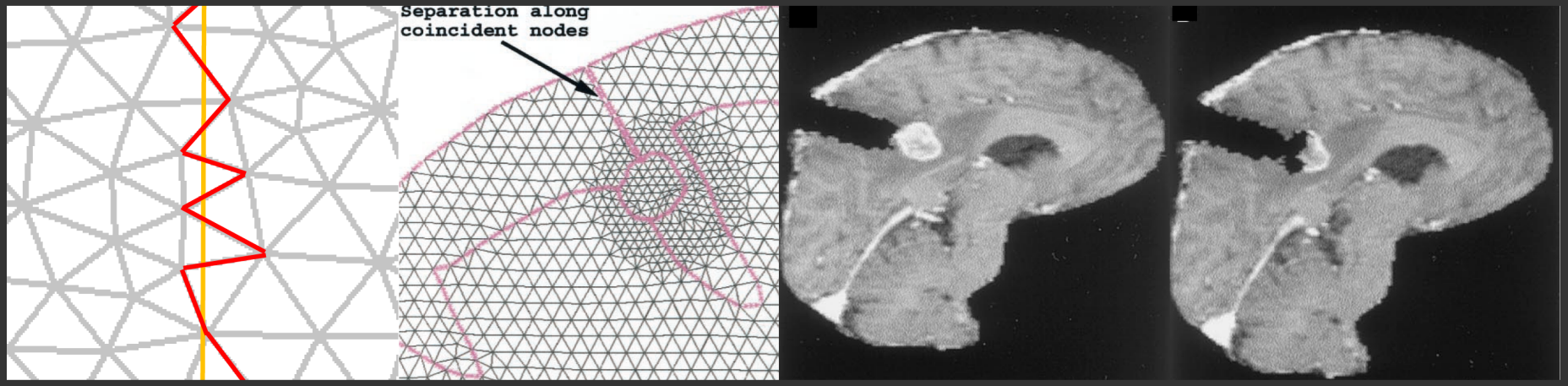
Miller, Wittek, et al.



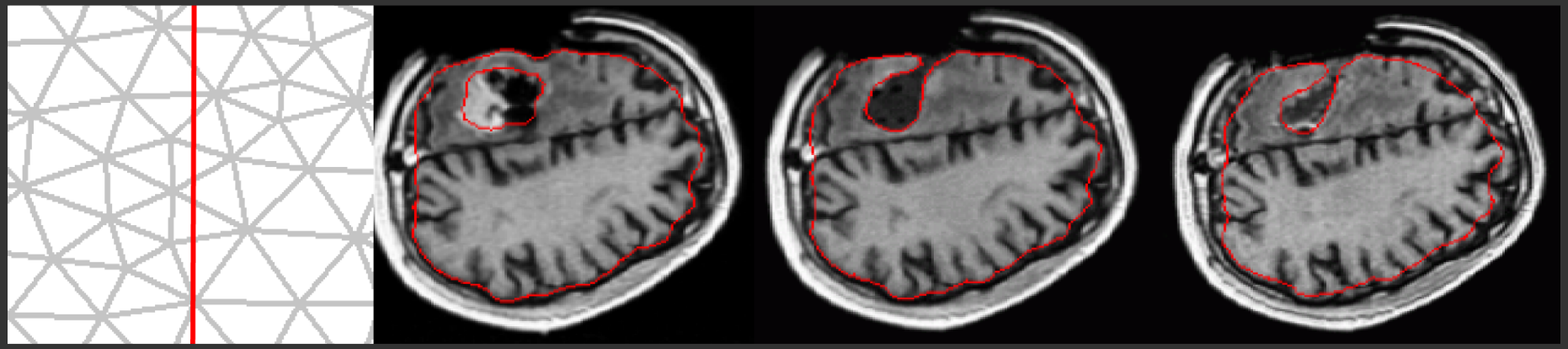
Kemper, Warfield, et al.

State-of-the-art

Limited research on successive deformations that include retraction and resection



Miga et al.



Ferrant et al.

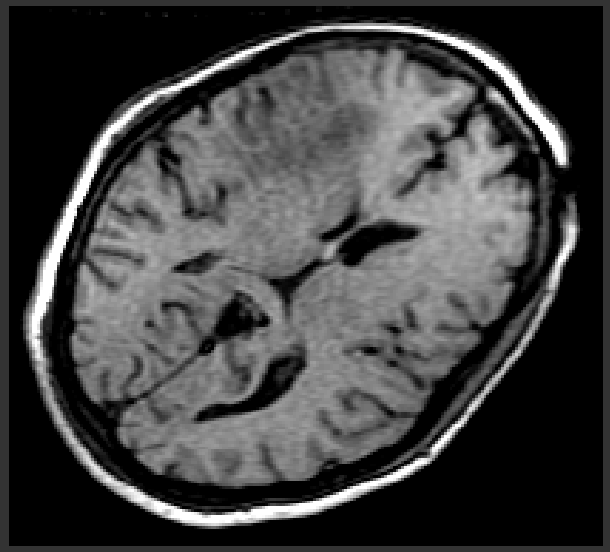
Challenge

To obtain a global framework

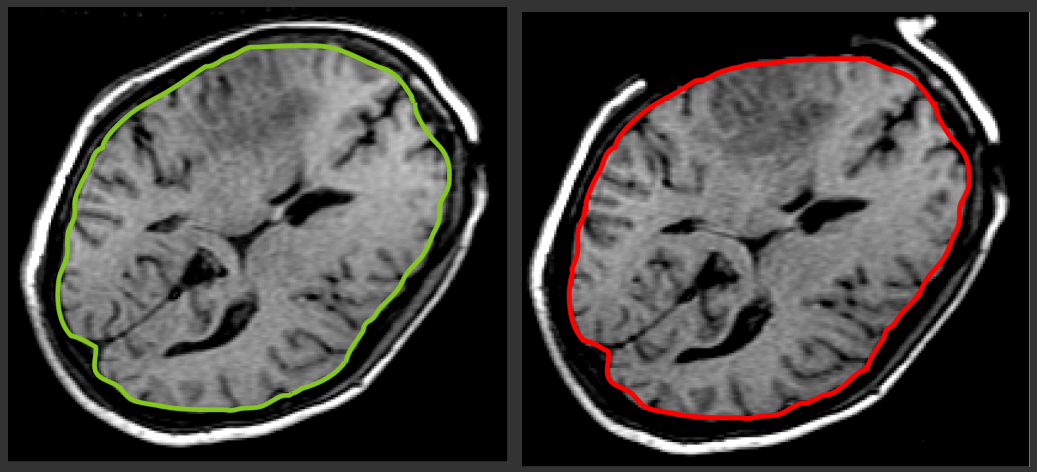
for updating preoperative images

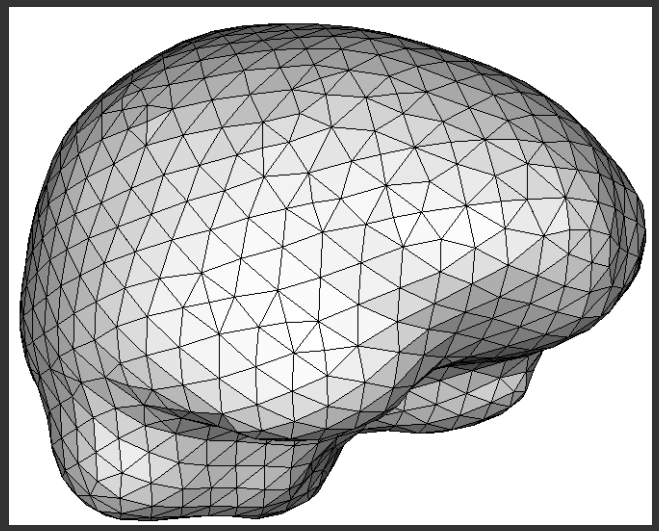
for any type of brain deformation

0.5 Tesla MR is chosen as intraoperative modality



Nonrigid registration is based on biomechanical models





Equations of solid mechanics solved with Finite Element Method (FEM)

Using biomechanical models, brain deformations are divided in 3 categories

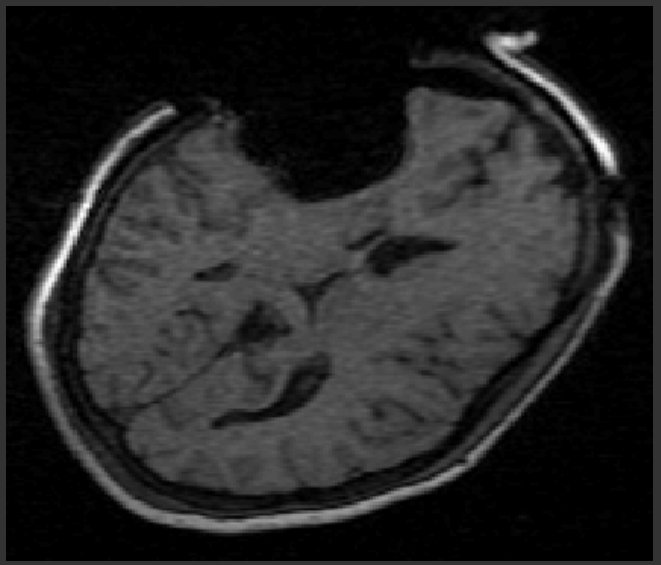
Shift

No topological change

Retraction

Cut (discontinuity)

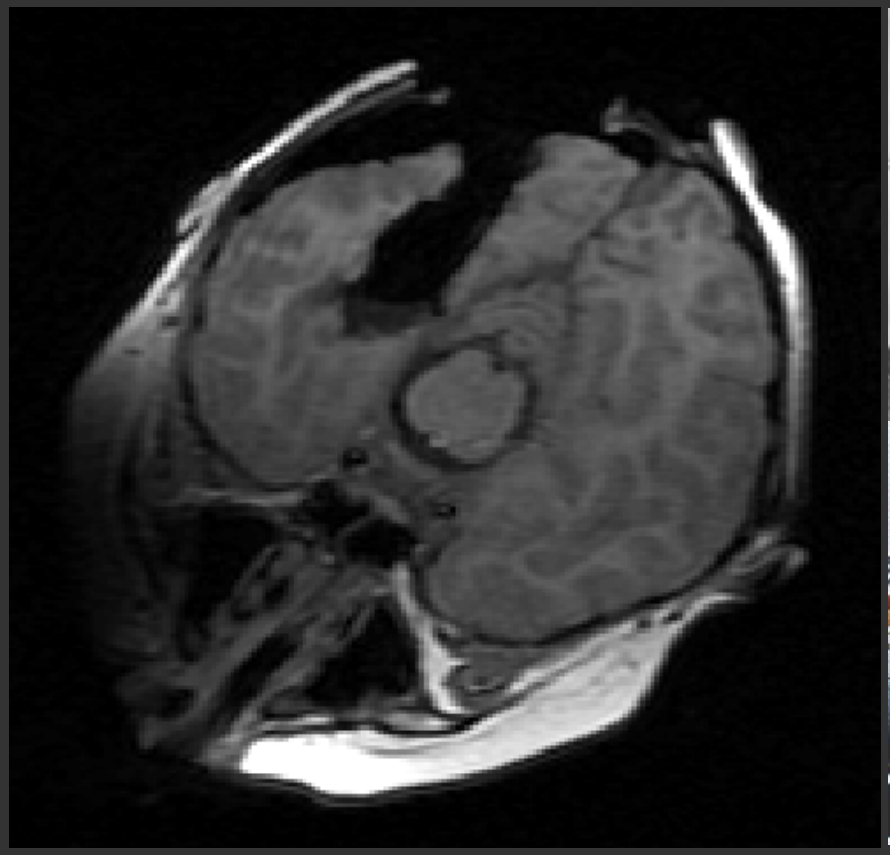
Resection

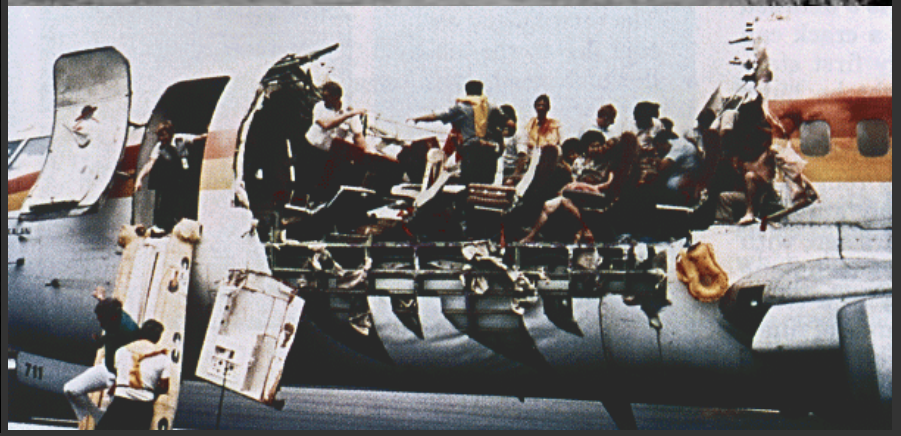


Cut (discontinuity) + Tissue removal

Modeling of cuts, retractions, and resections implies tissues discontinuities

Inspiration for solution: fracture mechanics!





eXtended Finite Element Method (XFEM)

XFEM introduced in 1999 by Moës et al.

Outline

- Developed framework for nonrigid registration
- Basic principles of XFEM
- Modeling of brain shift
- Modeling of successive resections
- Modeling of retraction
- Conclusions and perspectives

Outline

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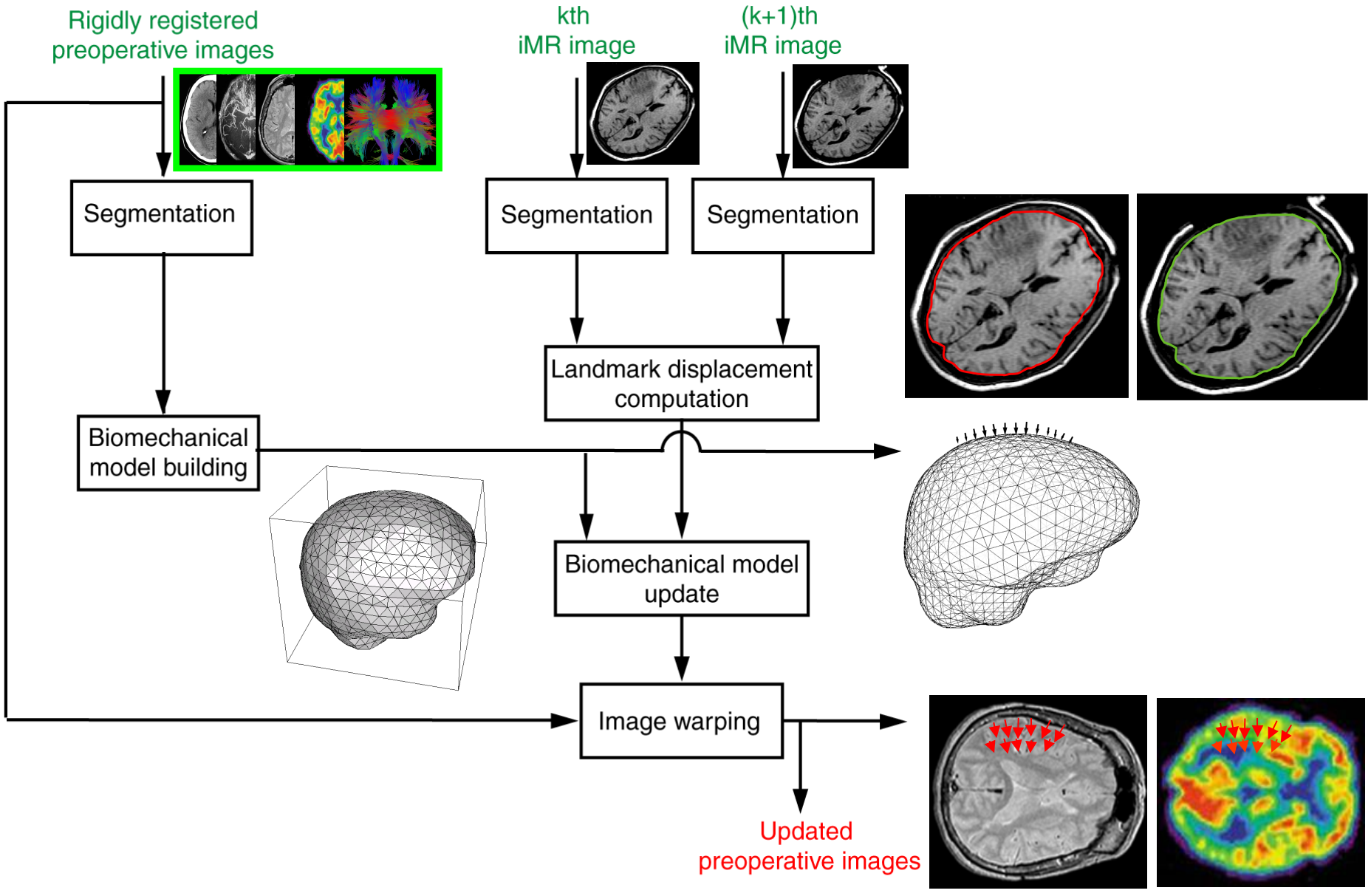
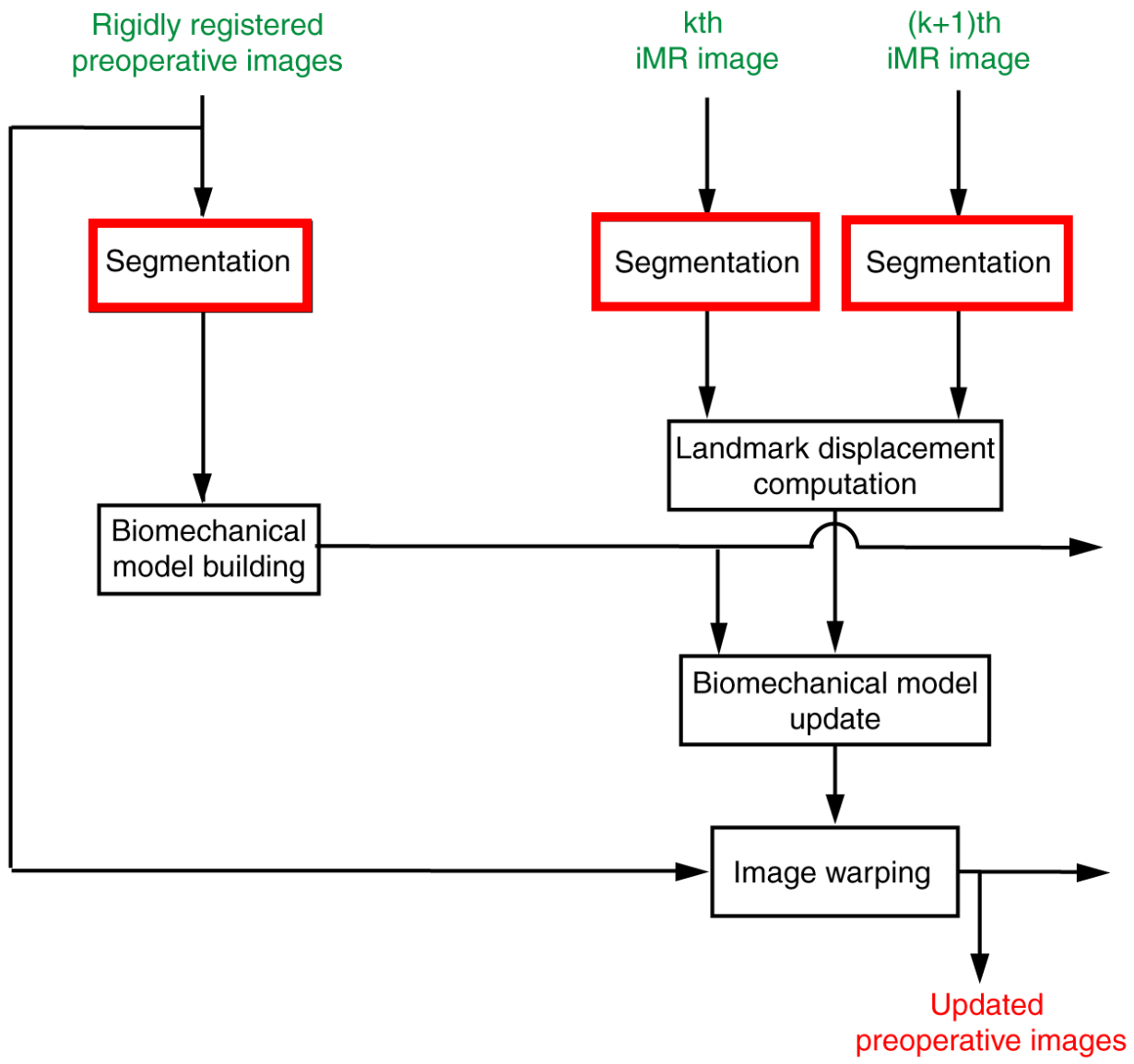
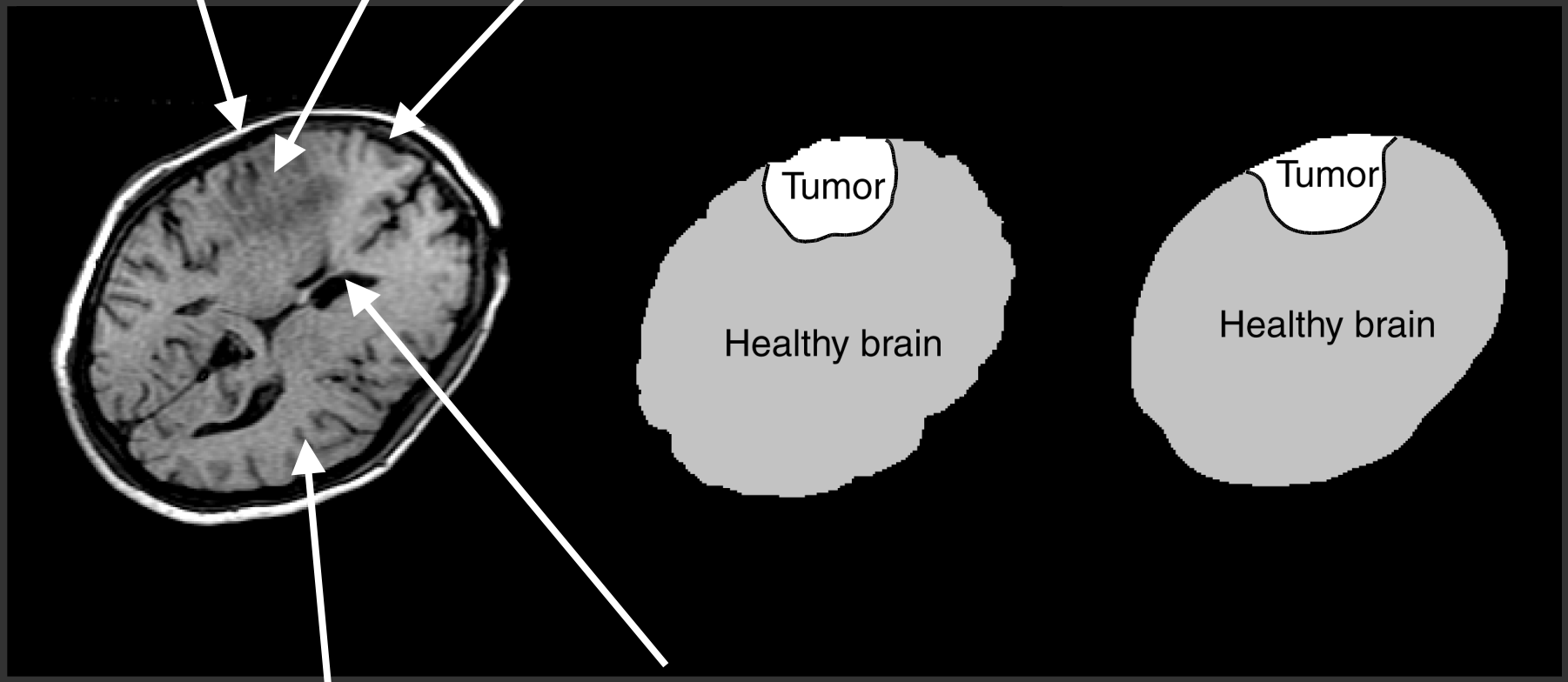
Nonrigid registration building blocks



Step 1: segmentation

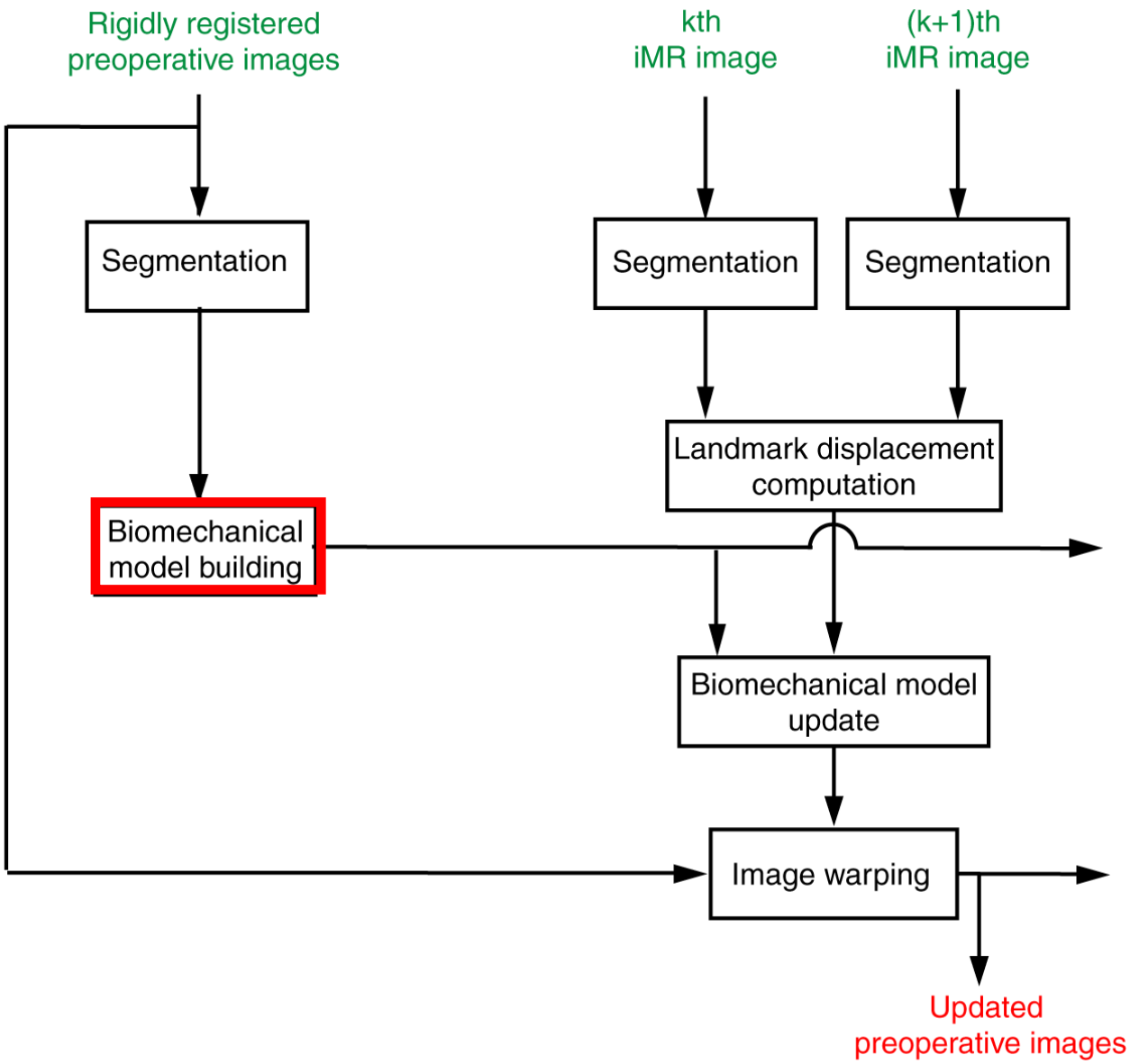


Segmentation of iMR images

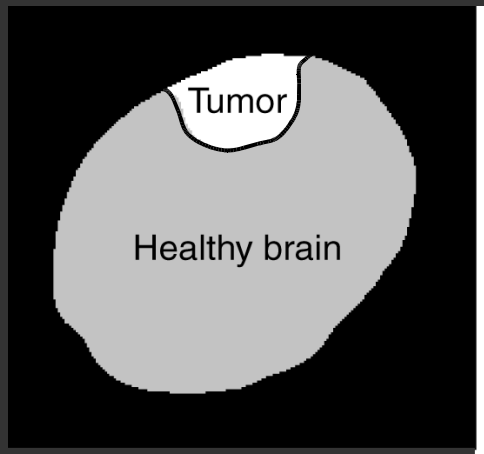


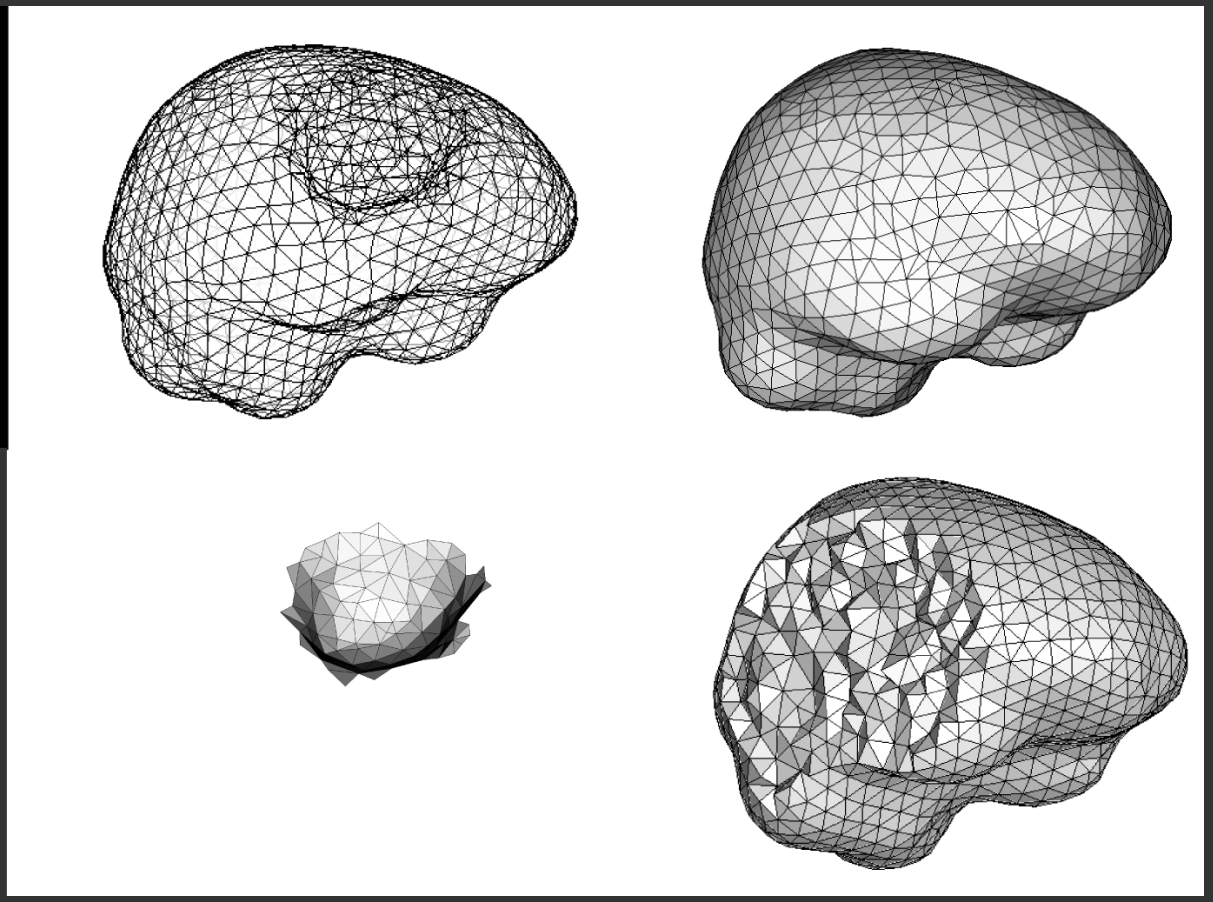
Segmentation performed manually using 3D Slicer and smoothed based on C++ library VTK

Step 2: biomechanical model building



A biomechanical model consists of a volume mesh and associated behavior laws



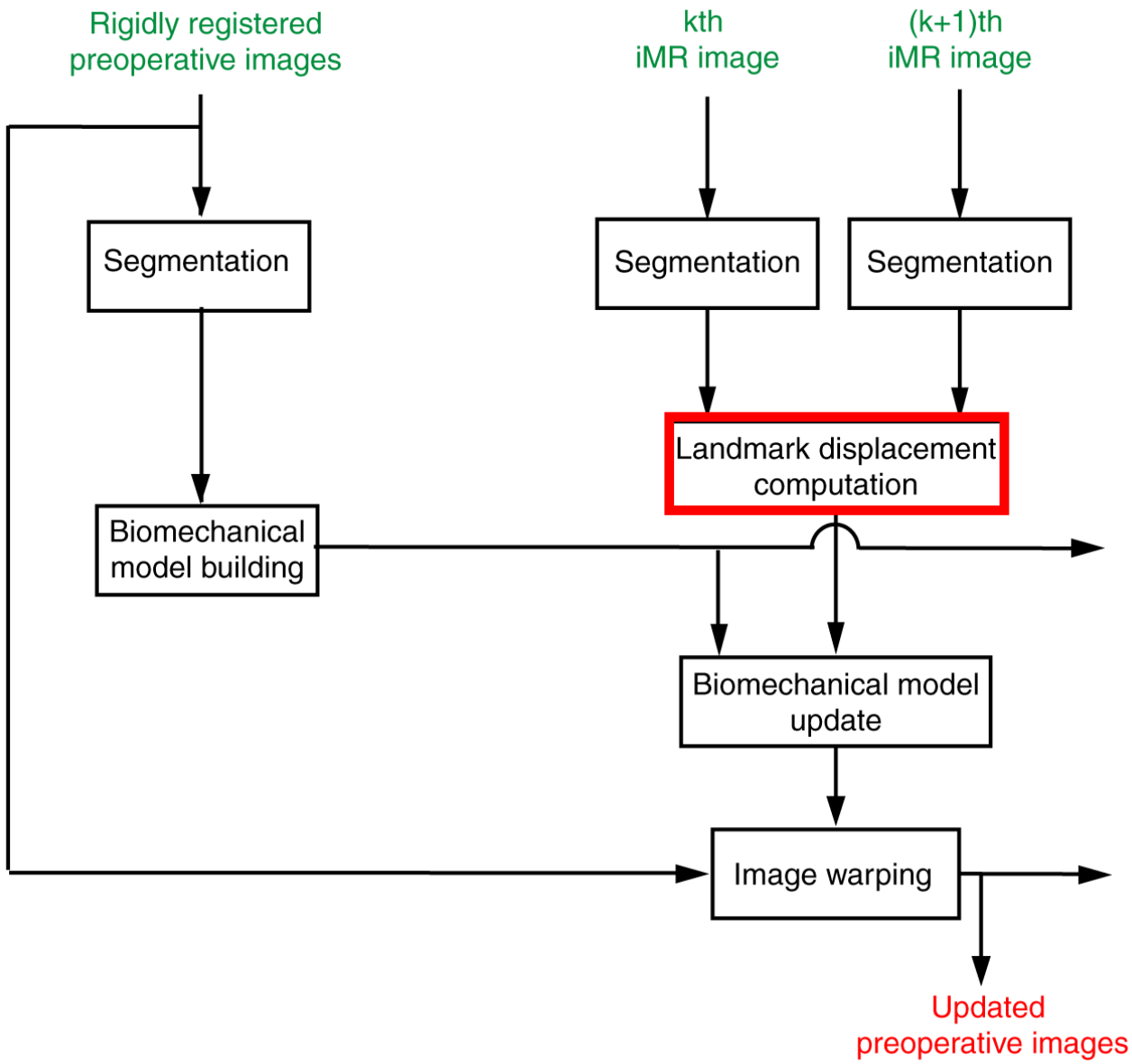


Surface meshing: Isosurf, Simmetrix, and methods implemented for PhD

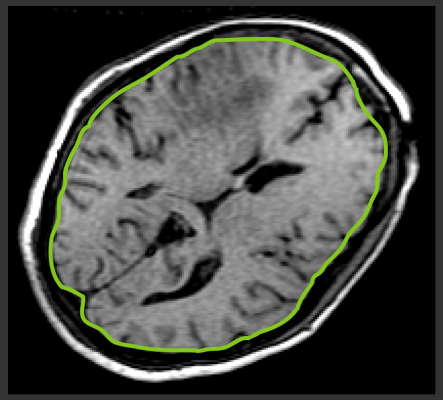
Volume meshing: Gmsh

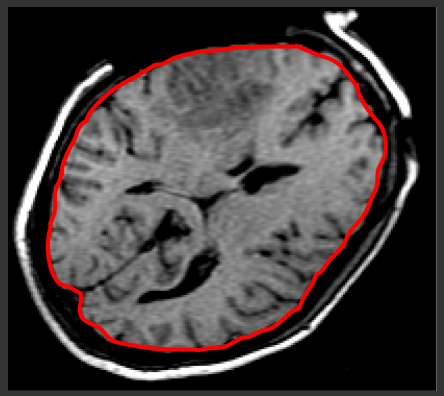
Constitutive law: linear elastic

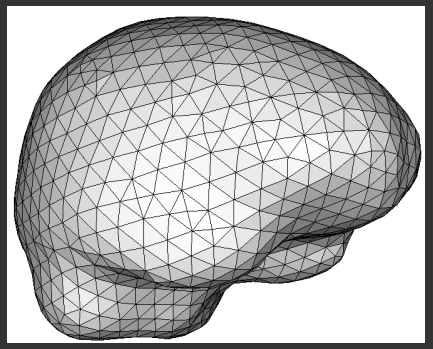
Step 3: landmark displacement computation



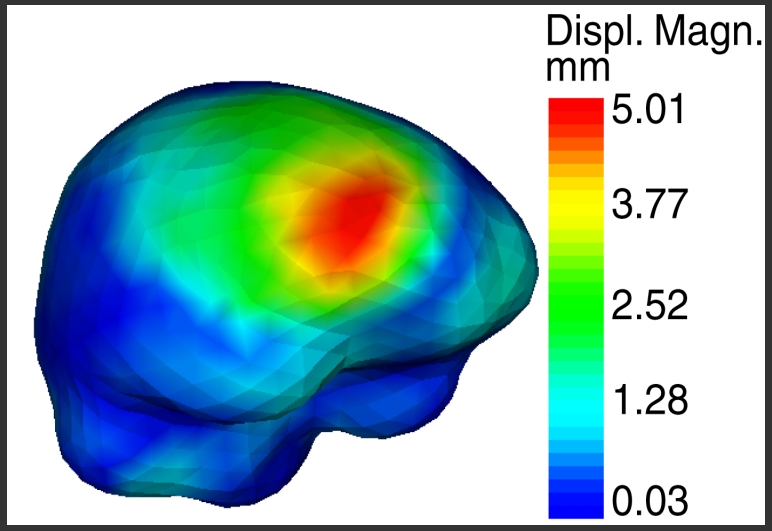
Surface matching is based on active surface algorithm

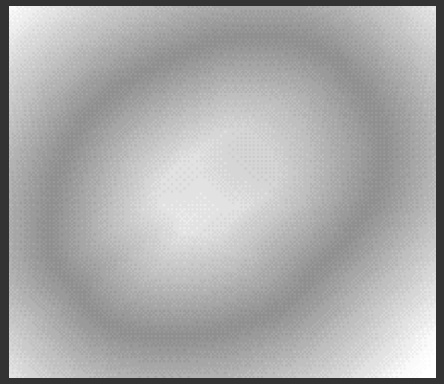






Internal forces
=
elasticity

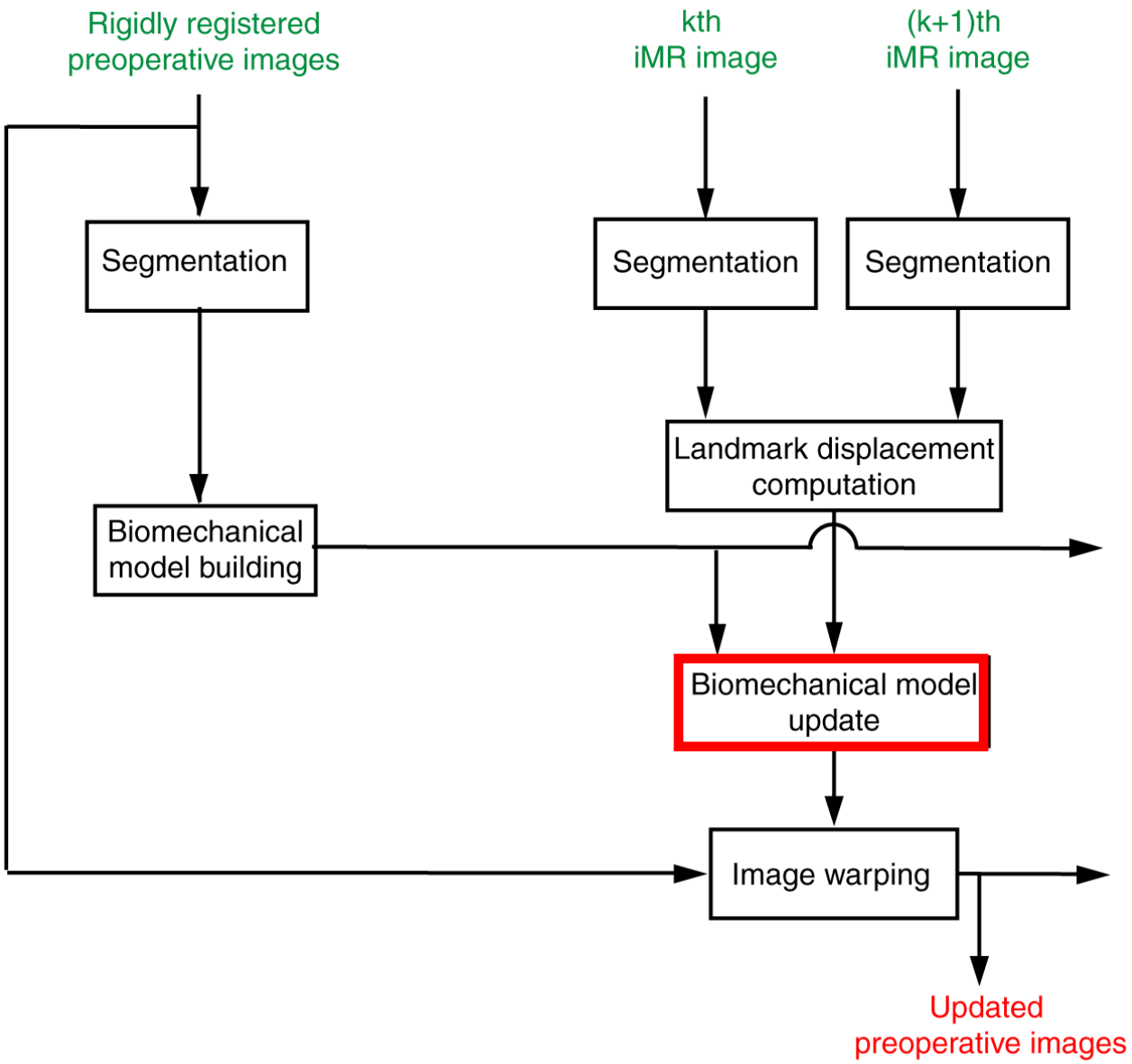




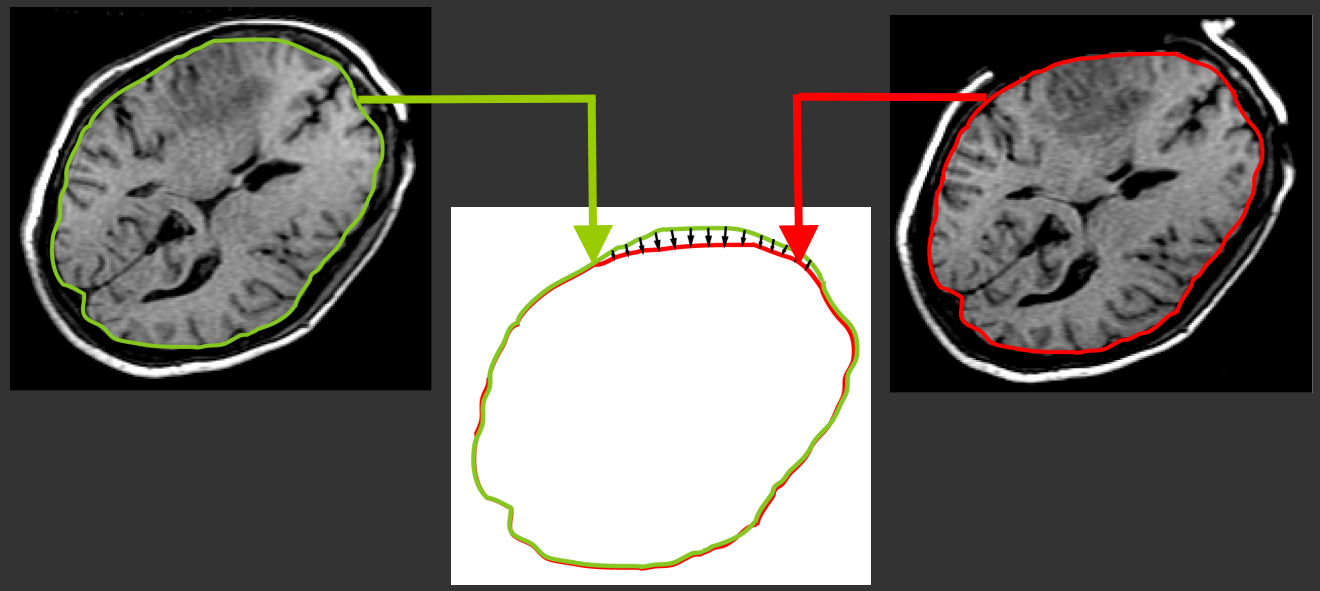
External forces based on distance map

Active surface algorithm implemented by M. Ferrant, Ferrant et al., 2001

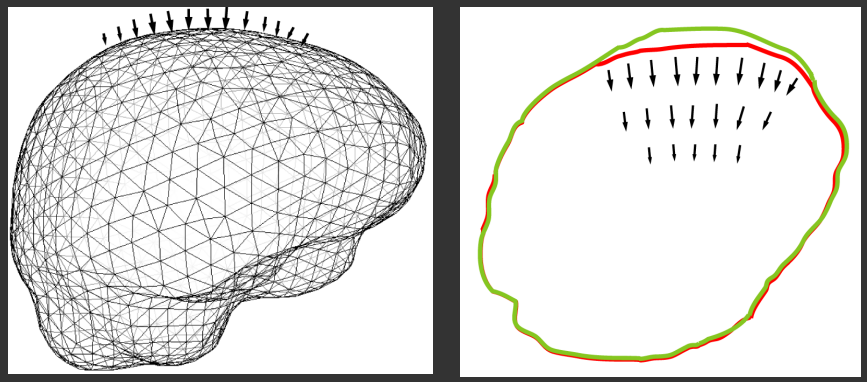
Step 4: biomechanical model update



Biomechanical model propagates surface displacement field inside volume

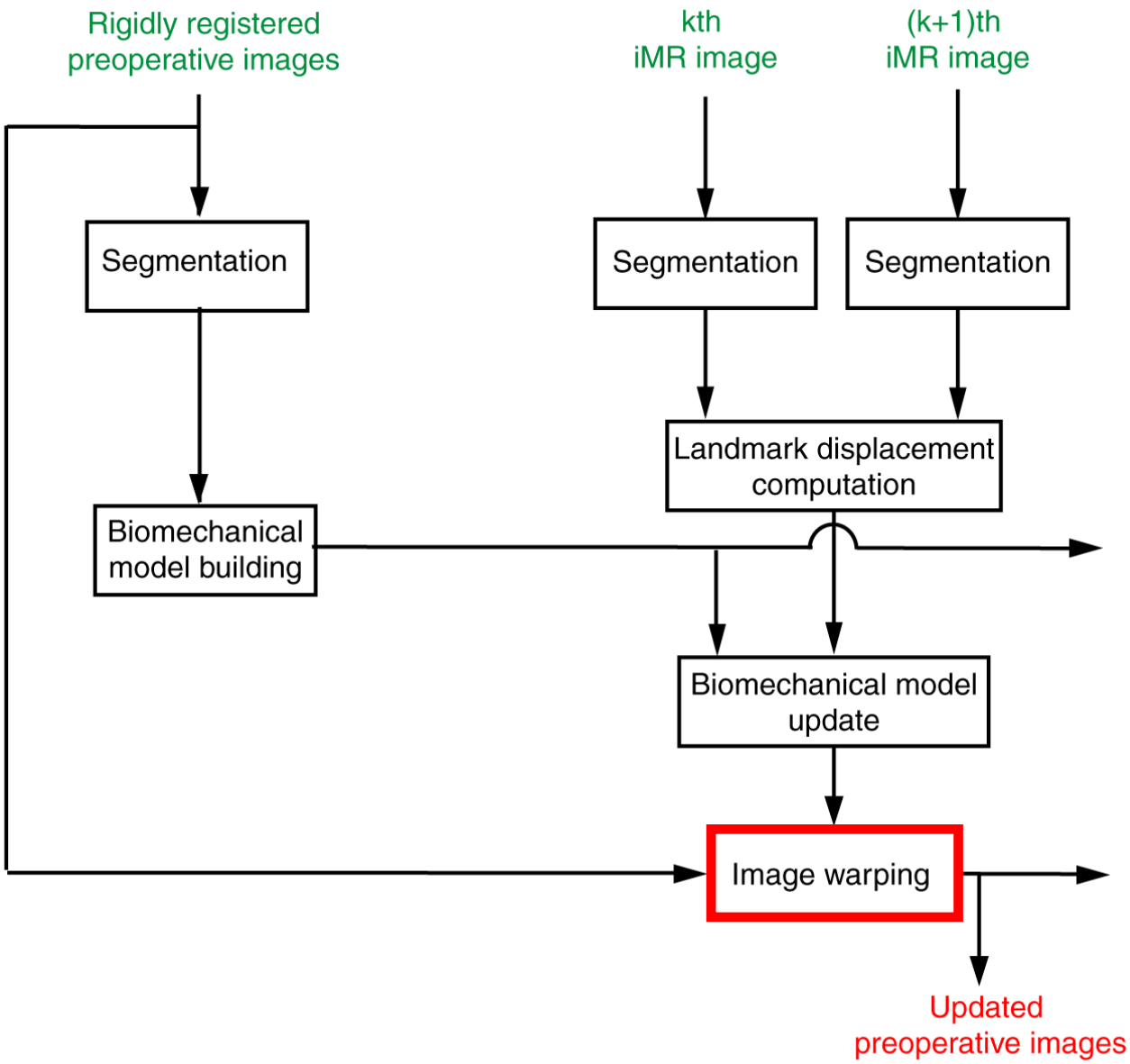


Linear formulation

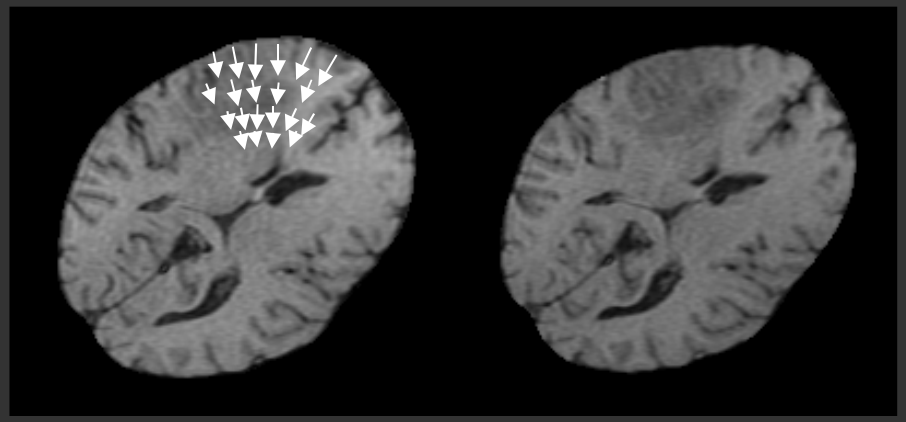


FEM: performed with Metafor (MN2L, LTAS, ULg)
XFEM: module implemented in Metafor for PhD

Step 5: image warping and validation



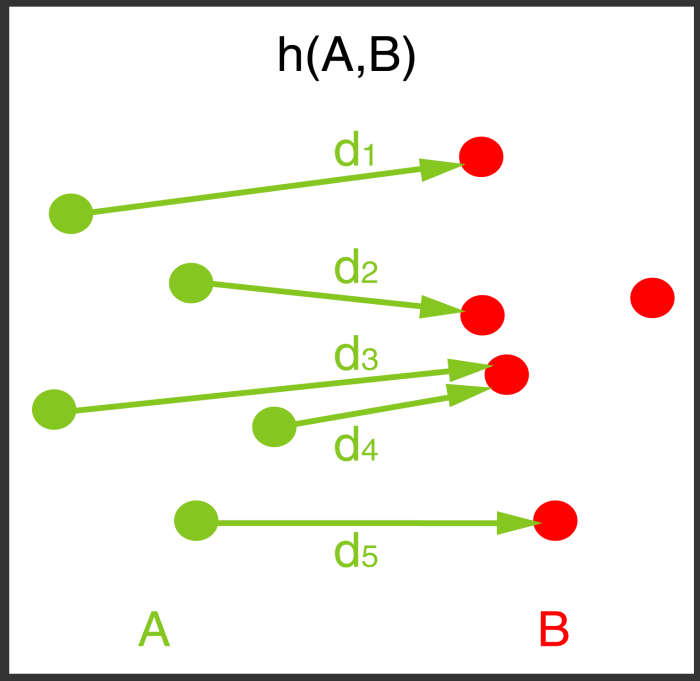
Validation is performed using Canny edges



Based on C++ library ITK

$$\mathcal{H}(A,B) = max(h(A,B), h(B,A))$$

$$h(A,B) = \frac{1}{N_a} \sum_{a \in A} d(a,B)$$



Outline

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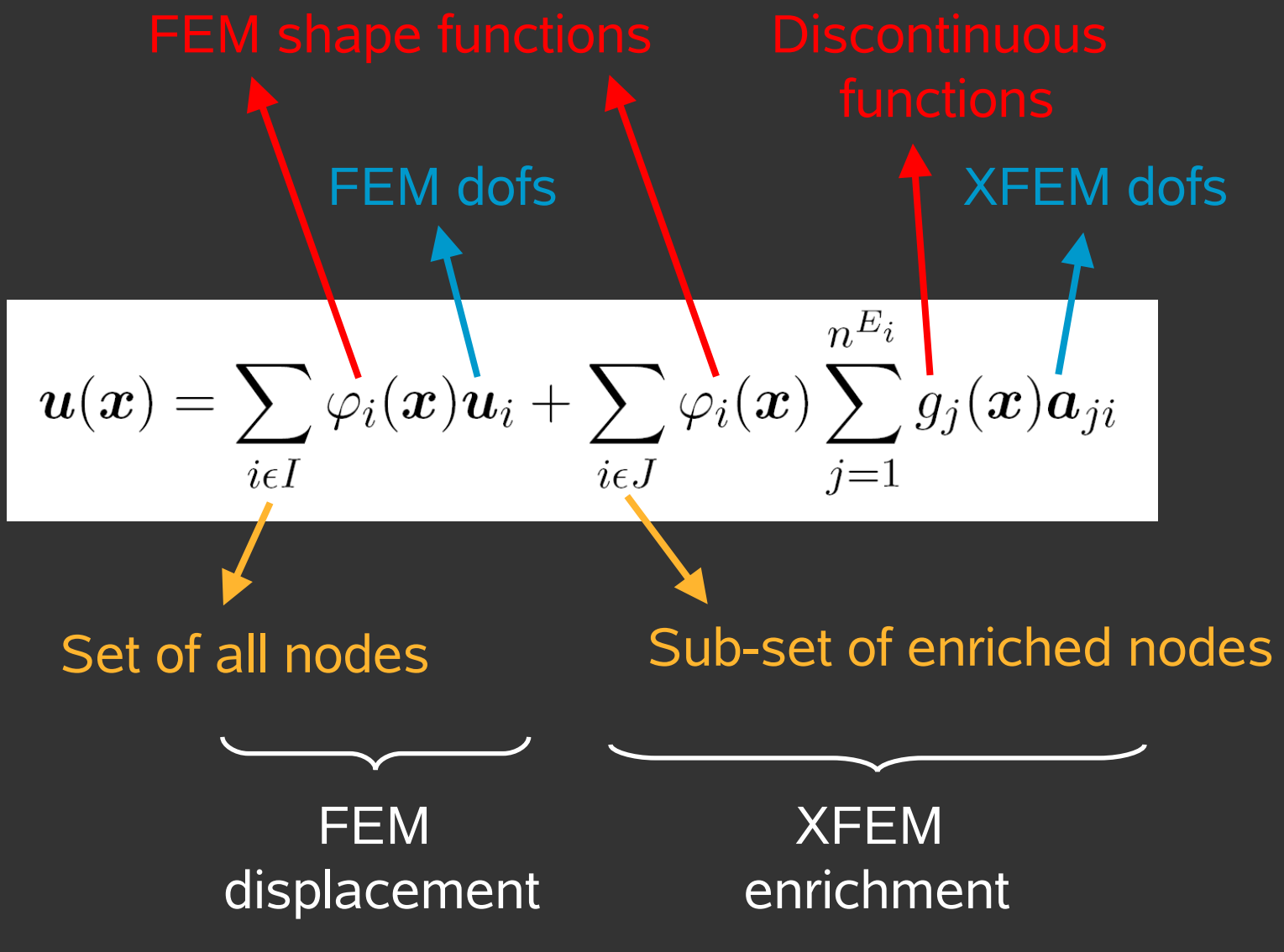
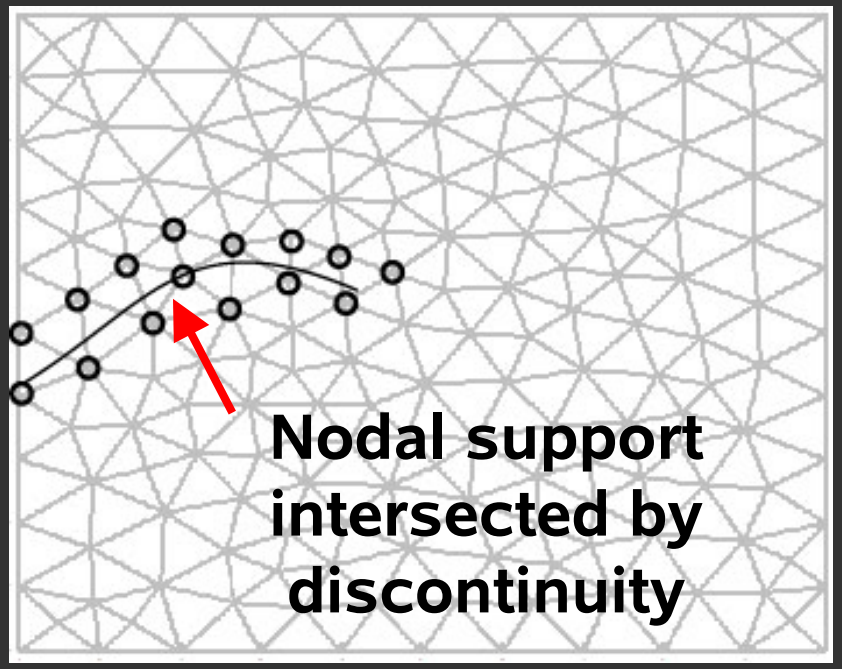
XFEM adds discontinuous functions to the FEM displacement field ("enrichment")



1st step of XFEM is to choose the nodes to enrich

$$\boldsymbol{u}(\boldsymbol{x}) = \sum_{i \epsilon I} \varphi_i(\boldsymbol{x}) \boldsymbol{u}_i + \sum_{i \epsilon J} \varphi_i(\boldsymbol{x}) \sum_{j=1}^{n^{E_i}} g_j(\boldsymbol{x}) \boldsymbol{a}_{ji}$$

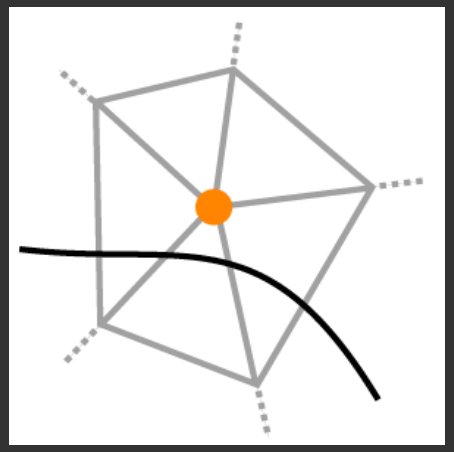
Displacement field solution: must be able to provide discontinuous behavior only around discontinuity

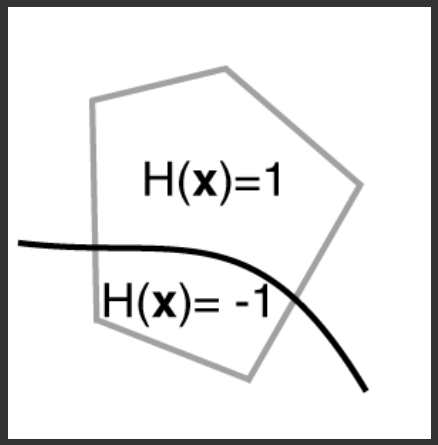


2nd step of XFEM is to choose the discontinuous functions (1)

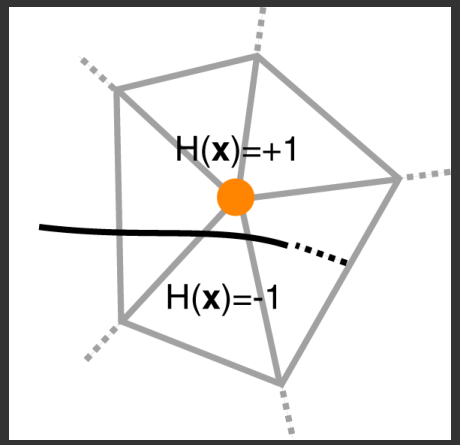
$$\boldsymbol{u}(\boldsymbol{x}) = \sum_{i \epsilon I} \varphi_i(\boldsymbol{x}) \boldsymbol{u}_i + \sum_{i \epsilon J} \varphi_i(\boldsymbol{x}) \sum_{j=1}^{n^{E_i}} g_j(\boldsymbol{x}) \boldsymbol{a}_{ji}$$

Node support entirely cut





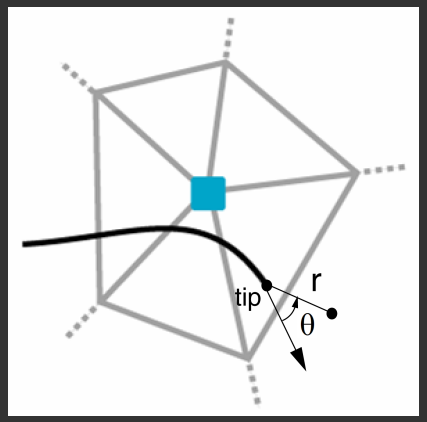
If not entirely cut



2nd step of XFEM is to choose the discontinuous functions (2)

$$\boldsymbol{u}(\boldsymbol{x}) = \sum_{i \epsilon I} \varphi_i(\boldsymbol{x}) \boldsymbol{u}_i + \sum_{i \epsilon J} \varphi_i(\boldsymbol{x}) \sum_{j=1}^{n^{E_i}} g_j(\boldsymbol{x}) \boldsymbol{a}_{ji}$$

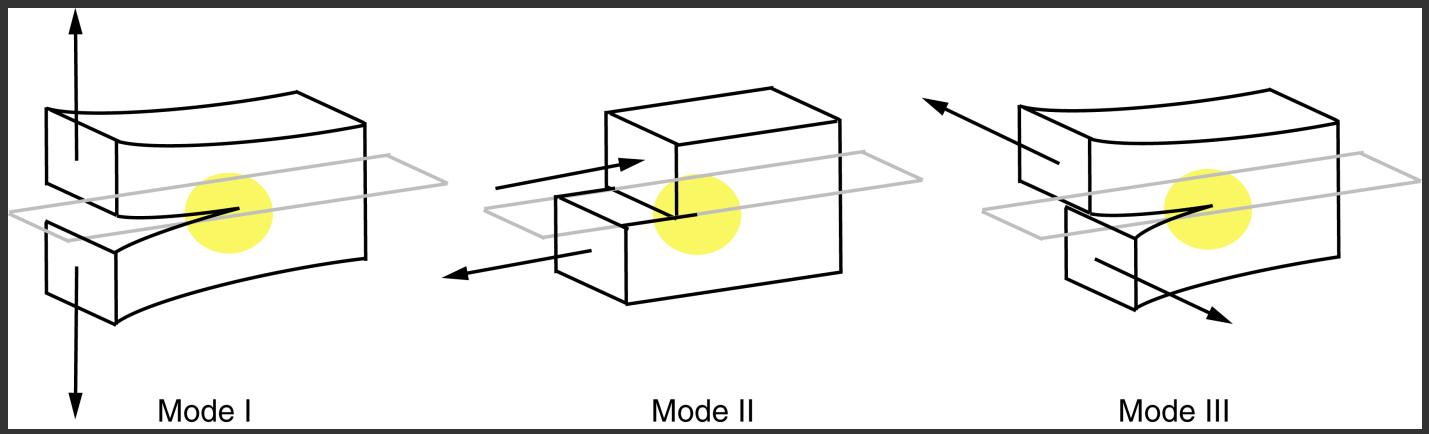
Node support contains tip



Functions: $\{F_l(r,\theta)\}_{l=1}^{4}$

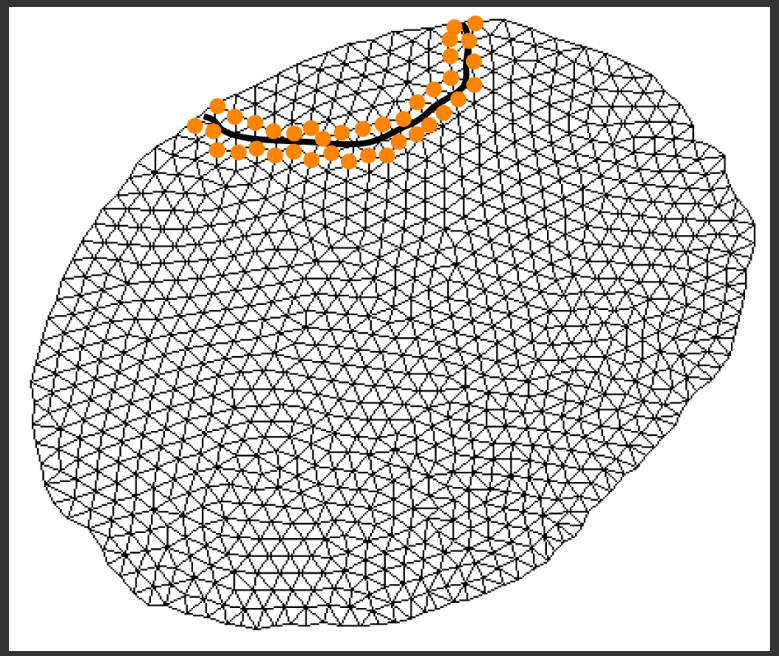
$$\{\sqrt{r}sin(\frac{\theta}{2}),\ \sqrt{r}cos(\frac{\theta}{2}),$$

$$\sqrt{r}sin(\frac{\theta}{2})sin(\theta),\ \sqrt{r}cos(\frac{\theta}{2})sin(\theta)\}$$

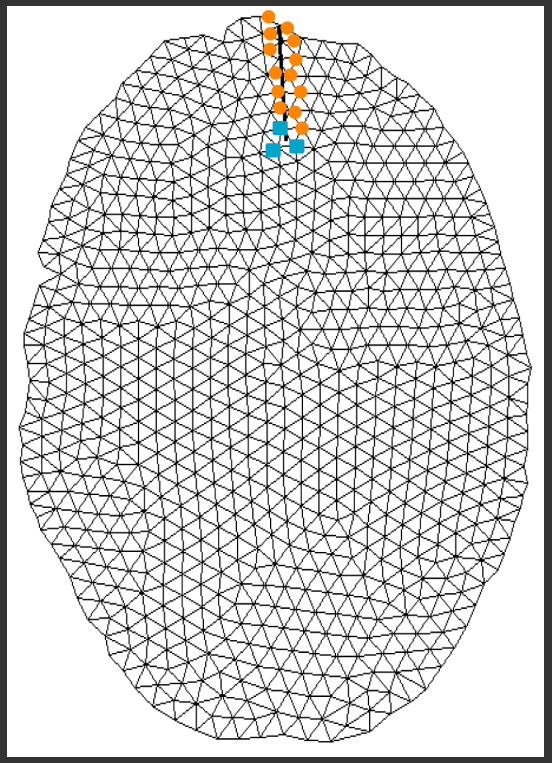


XFEM for brain tissue discontinuities

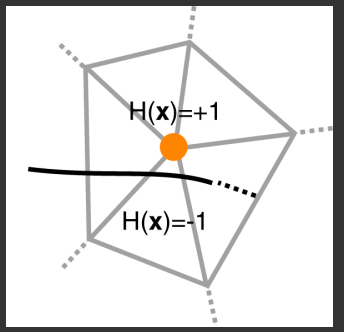
Resection



Retraction



2D



3D

2D retraction and resection modeling, Vigneron et al., 2008, accepted, Computer Aided Surgery

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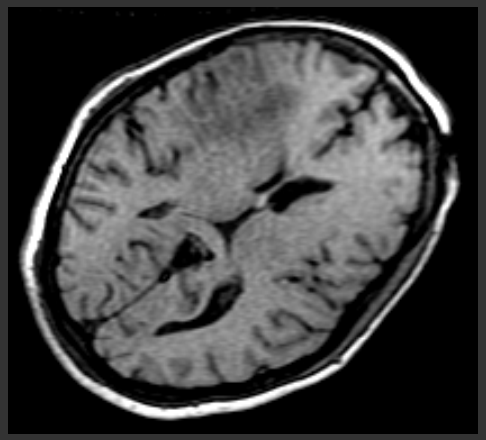
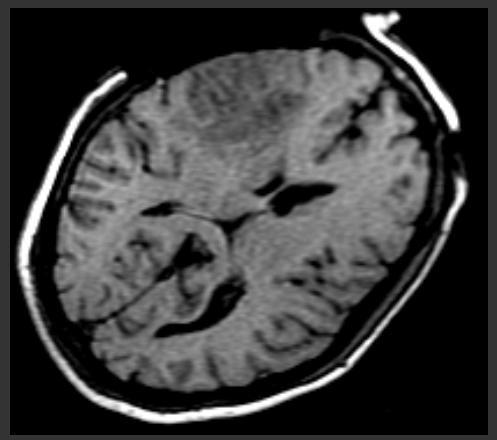
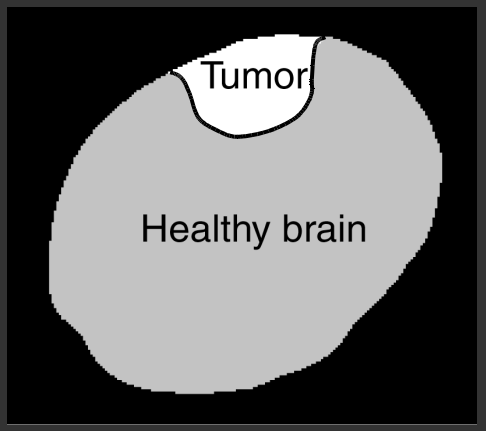
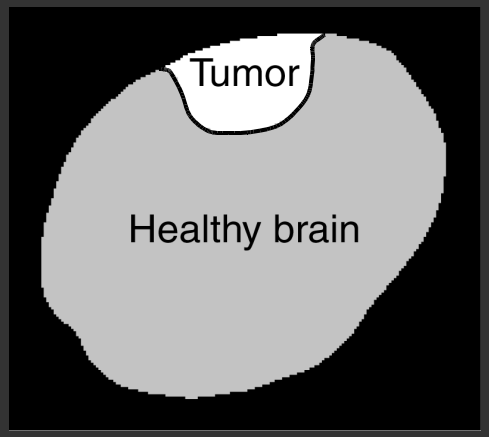
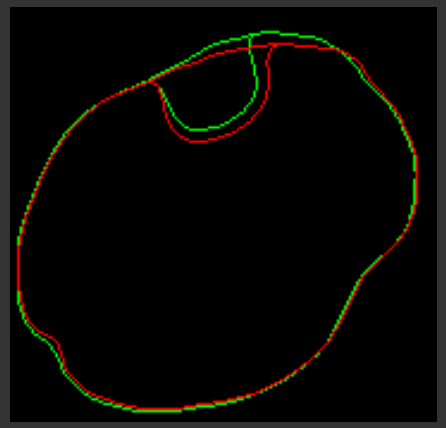
Two surface landmarks are chosen

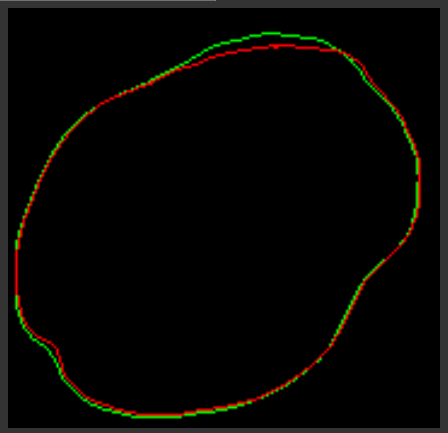


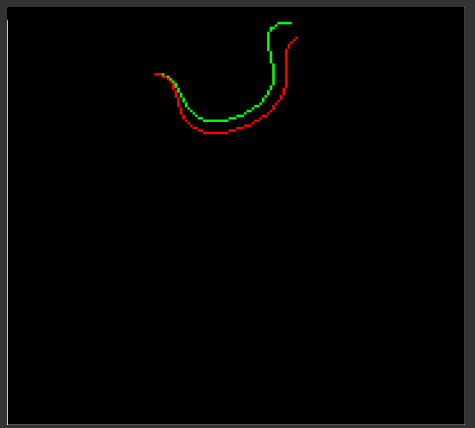




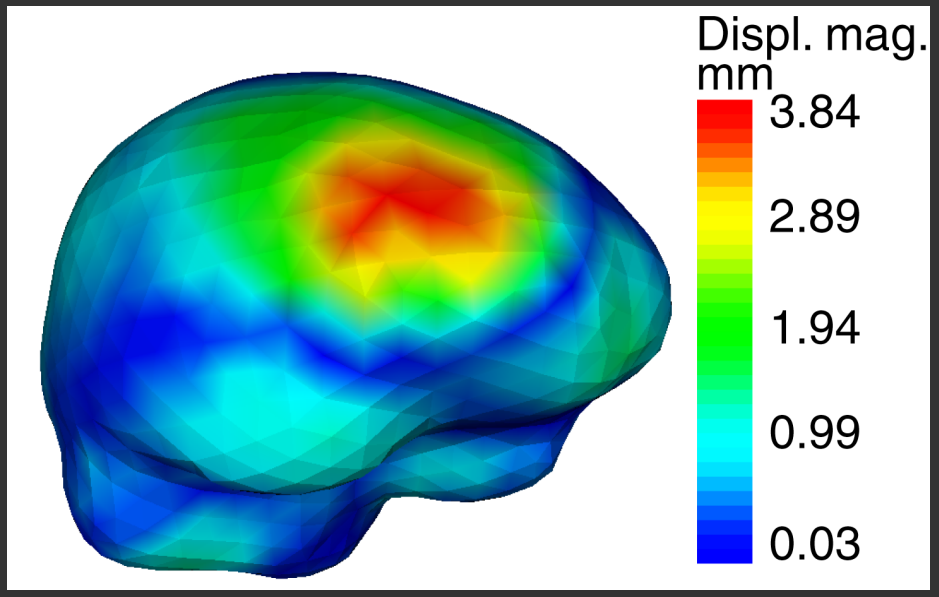


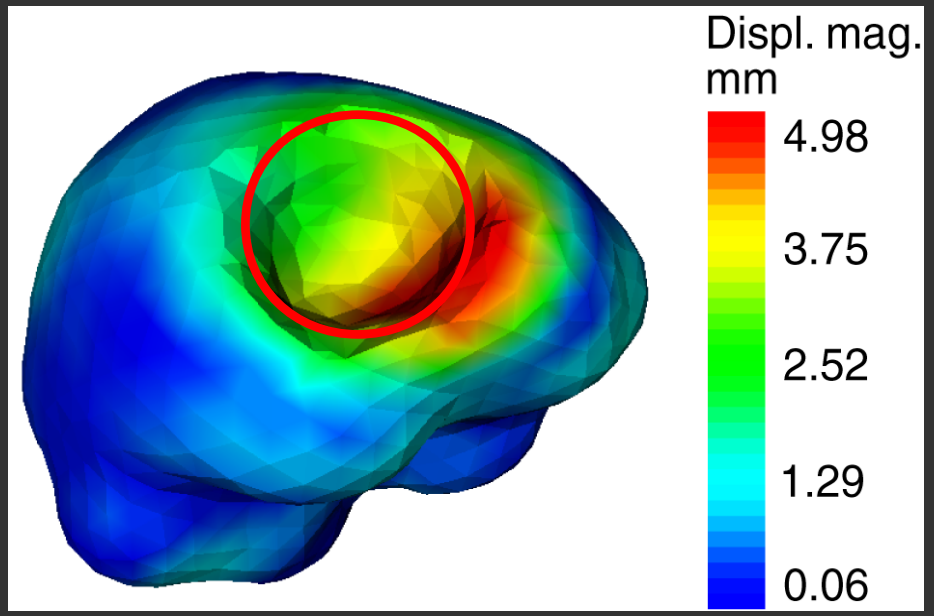




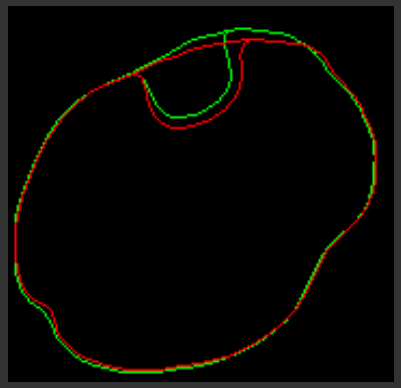


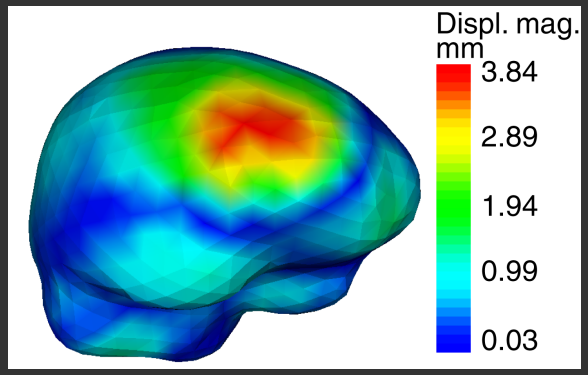
Surface displacement field of whole- and healthy-brain region boundaries

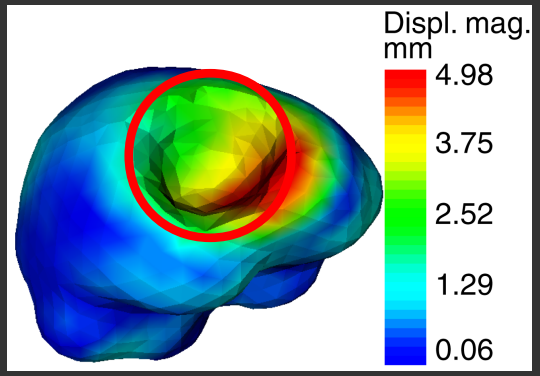




Biomechanical volume deformation for brain shift modeling







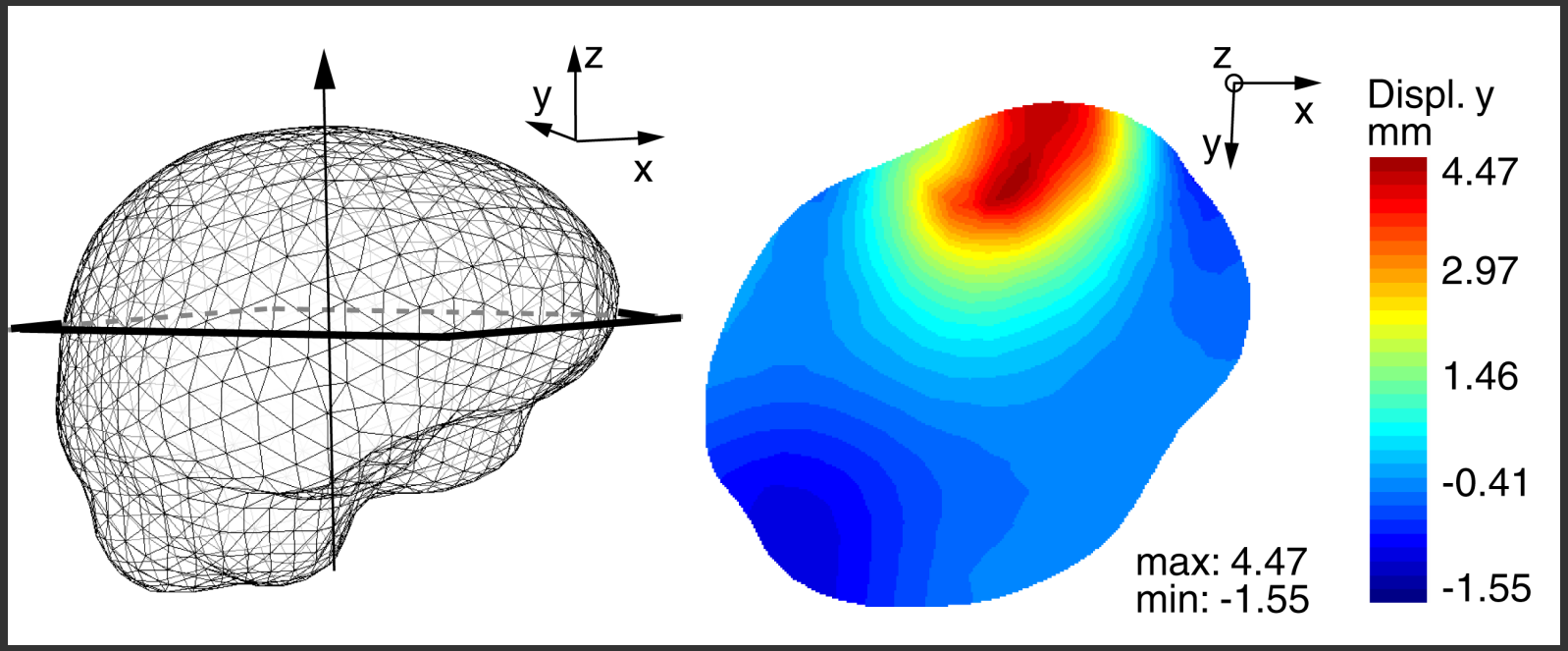
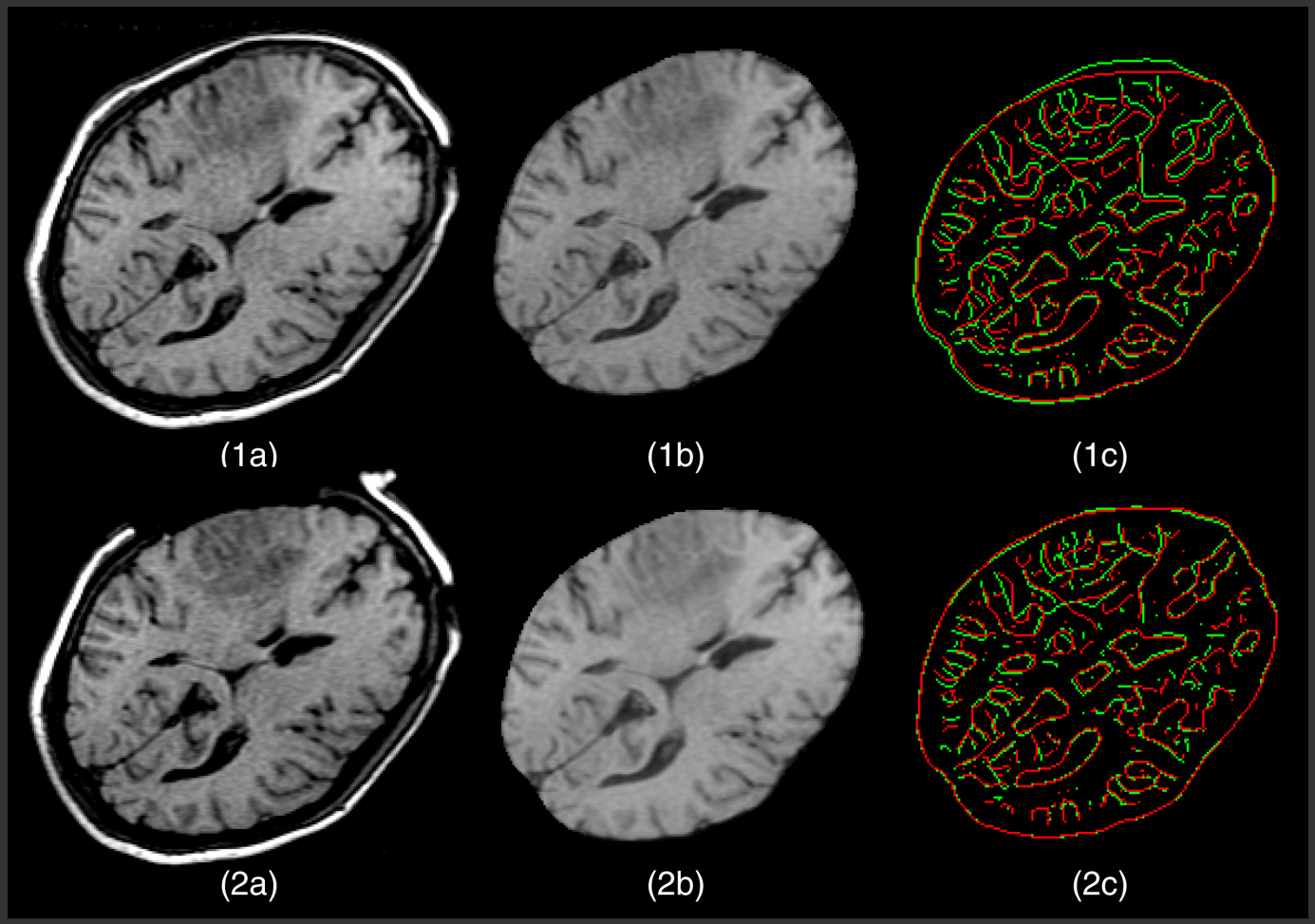
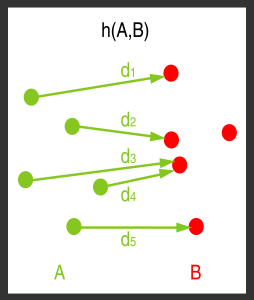


Image update and validation for brain shift modeling





Modified Hausdorff Distance: 1.24 mm->1.08 mm

Vigneron et al., 2008, submitted to Journal of Computational and Applied Mathematics

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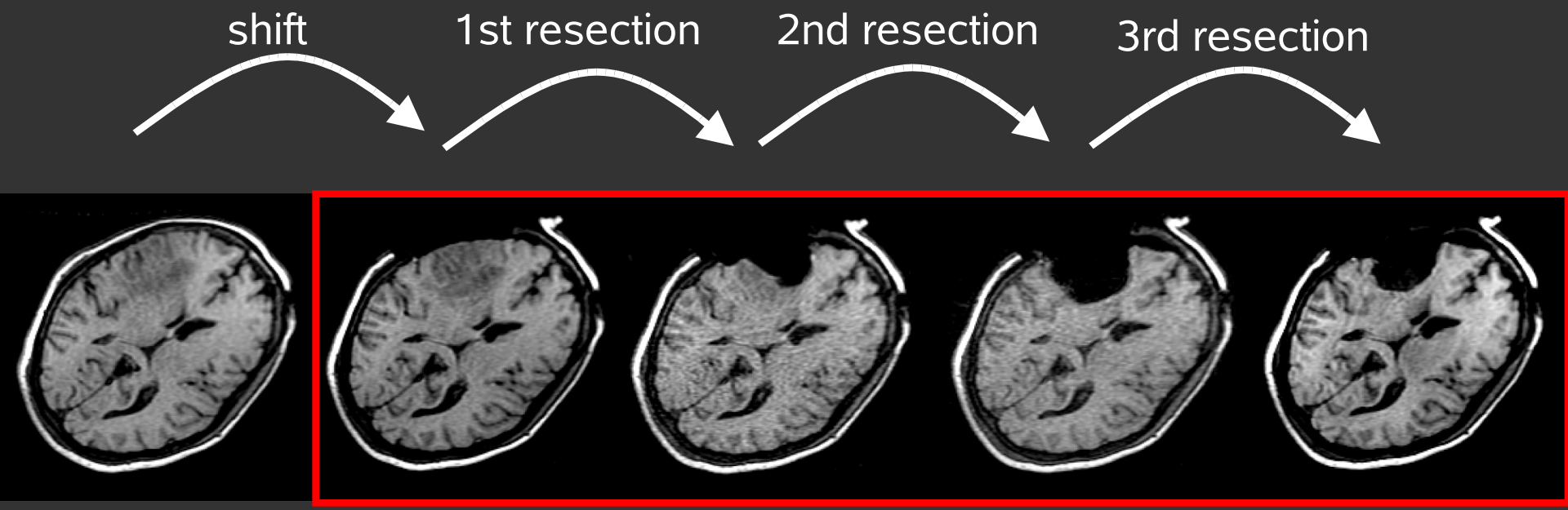
Illustration of successive resections

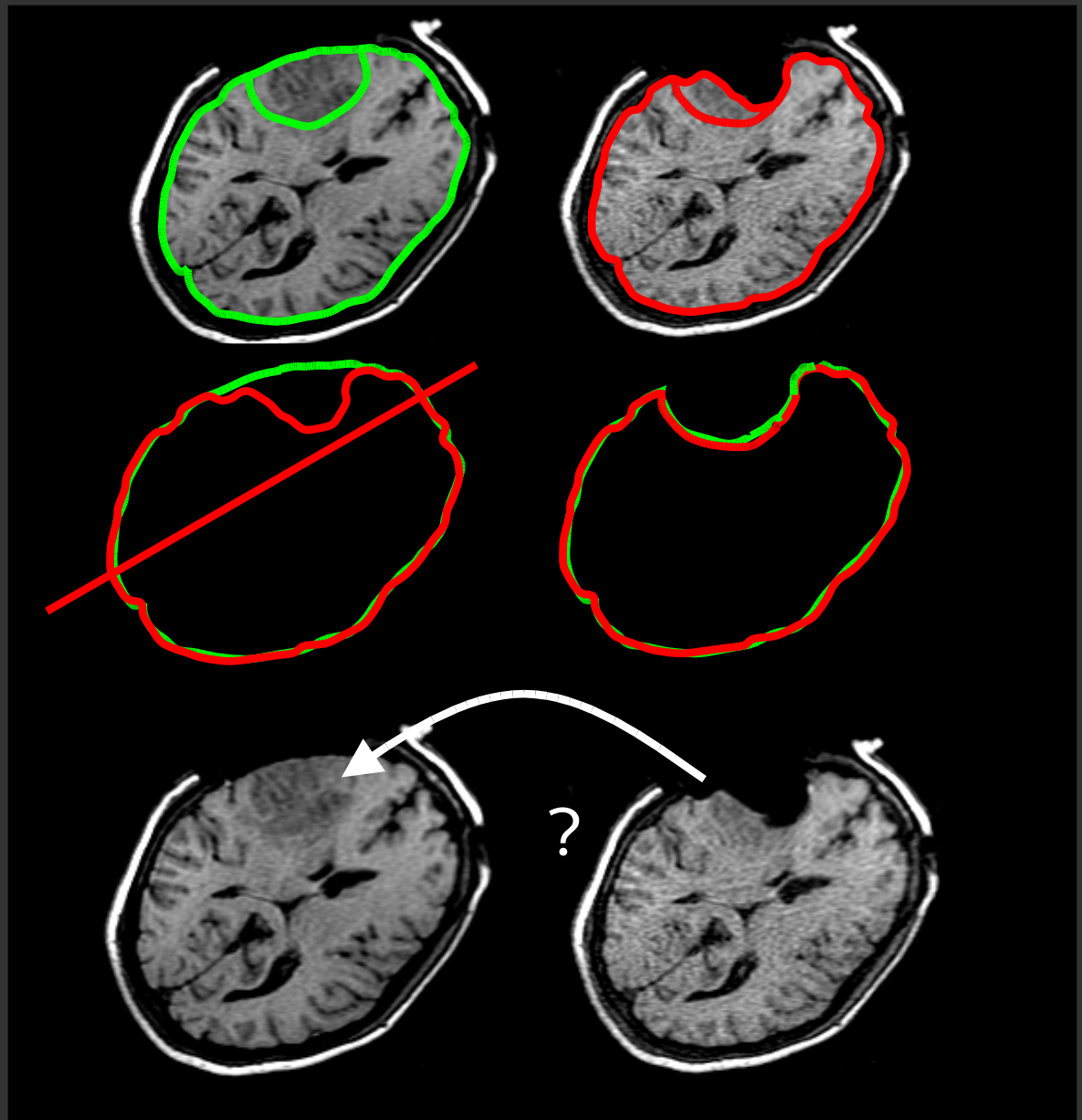


Cut (discontinuity) + Tissue removal

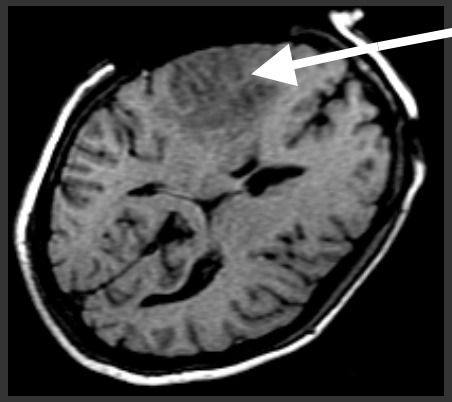
Implication of resection on modeling

Cut

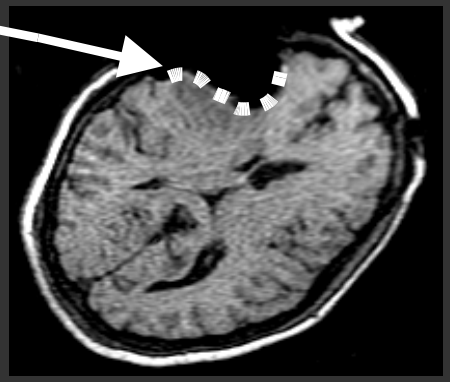
Tissue removal



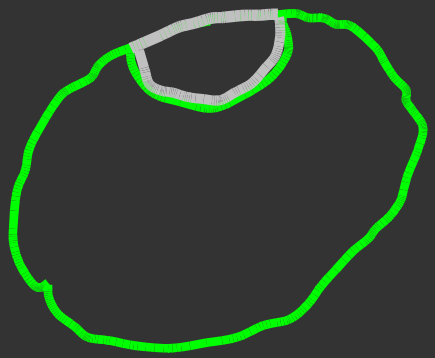
1st resection modeling

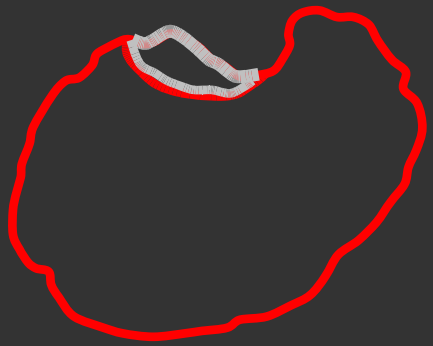


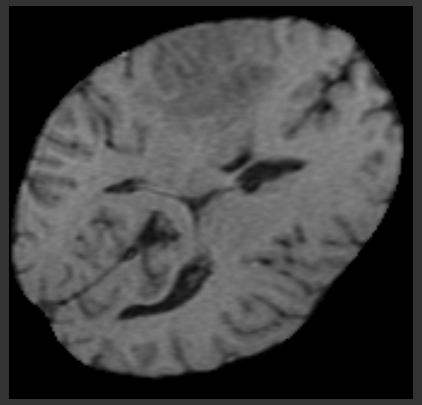
?

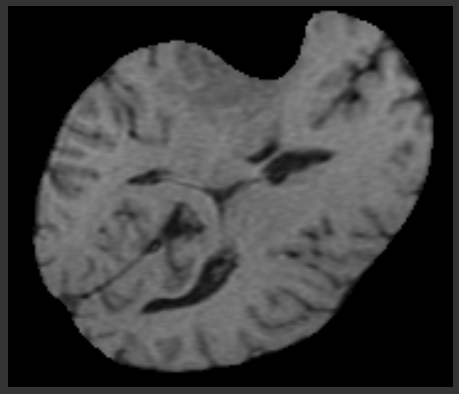


=>No cut modeled
=>FEM

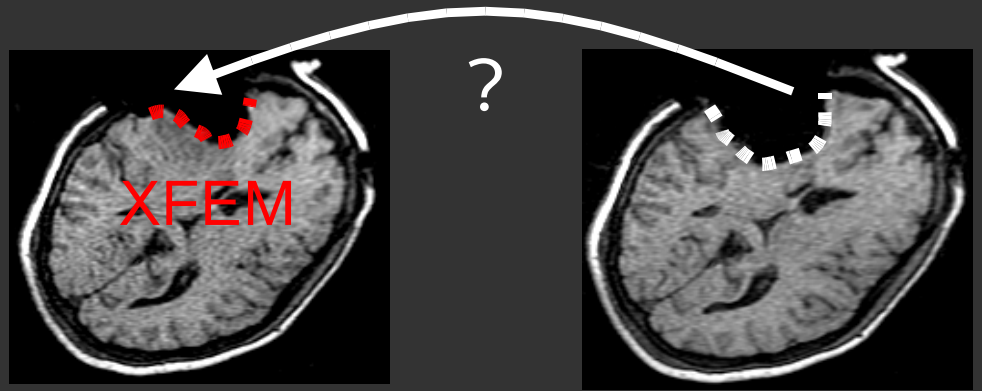


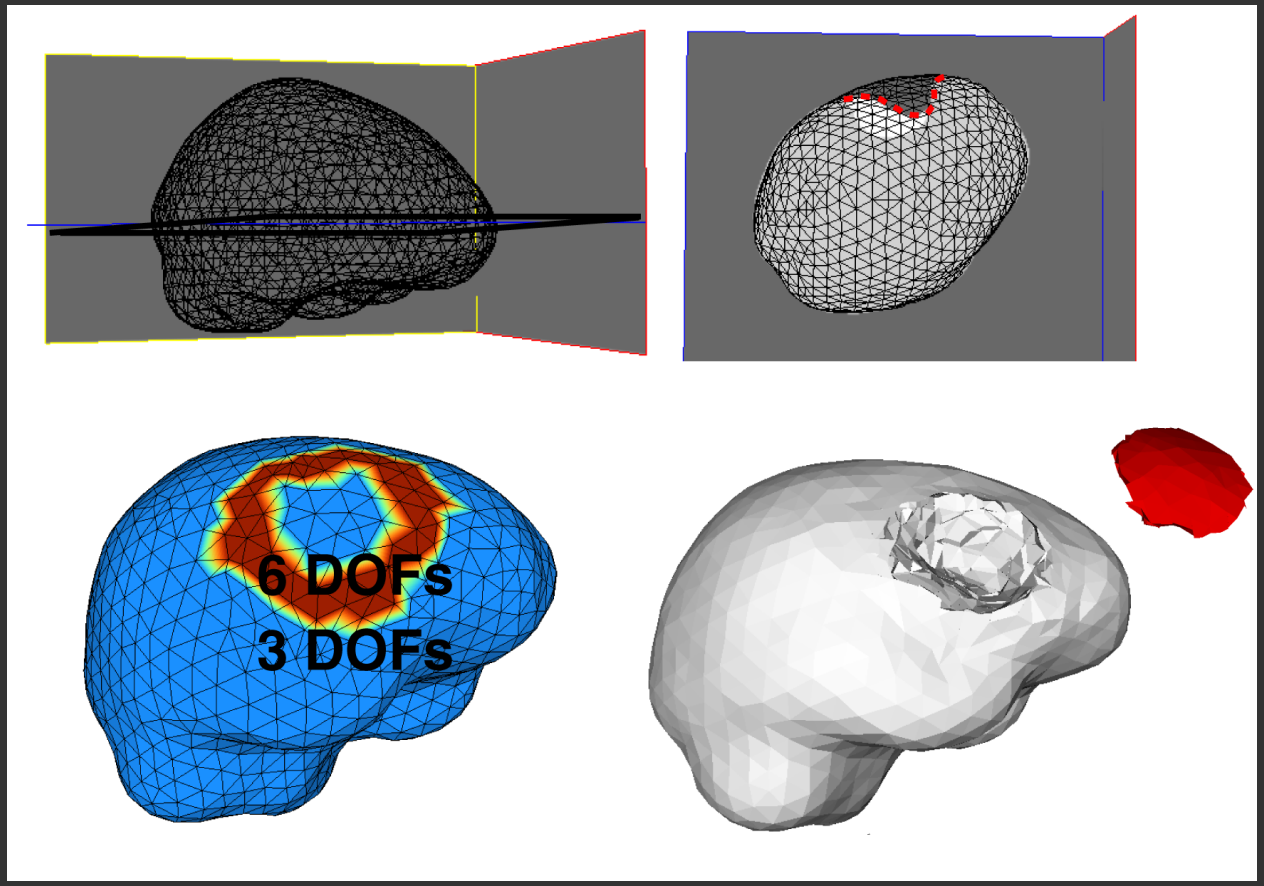




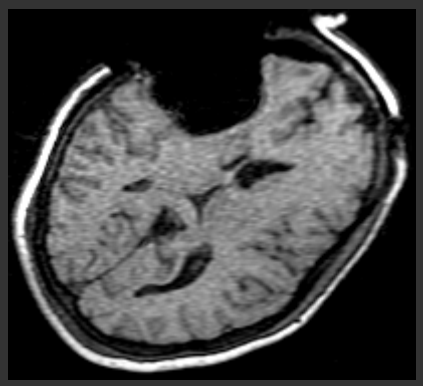
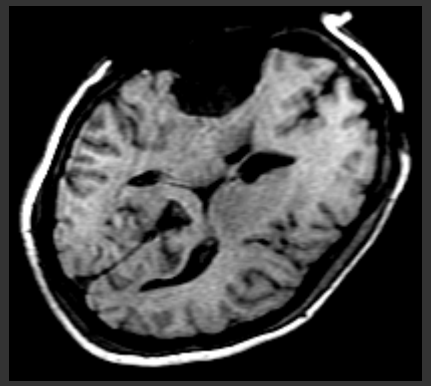


2nd resection modeling

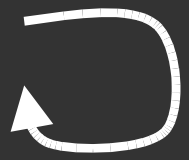




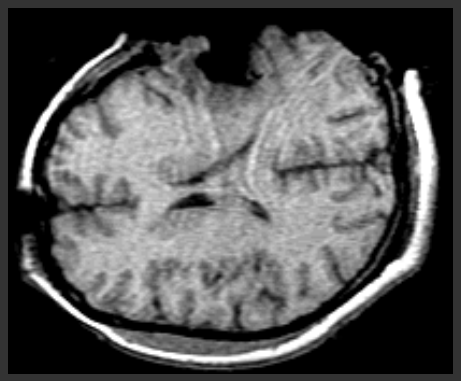
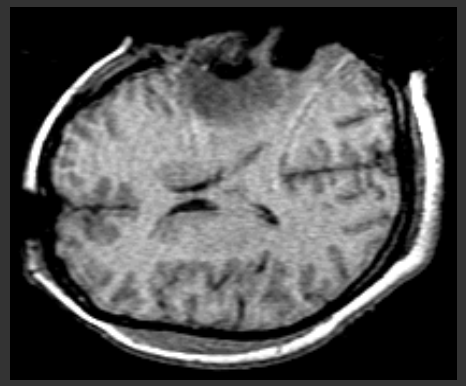
3rd resection modeling

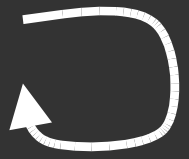
Resection complete



FEM-based
1st resection modeling

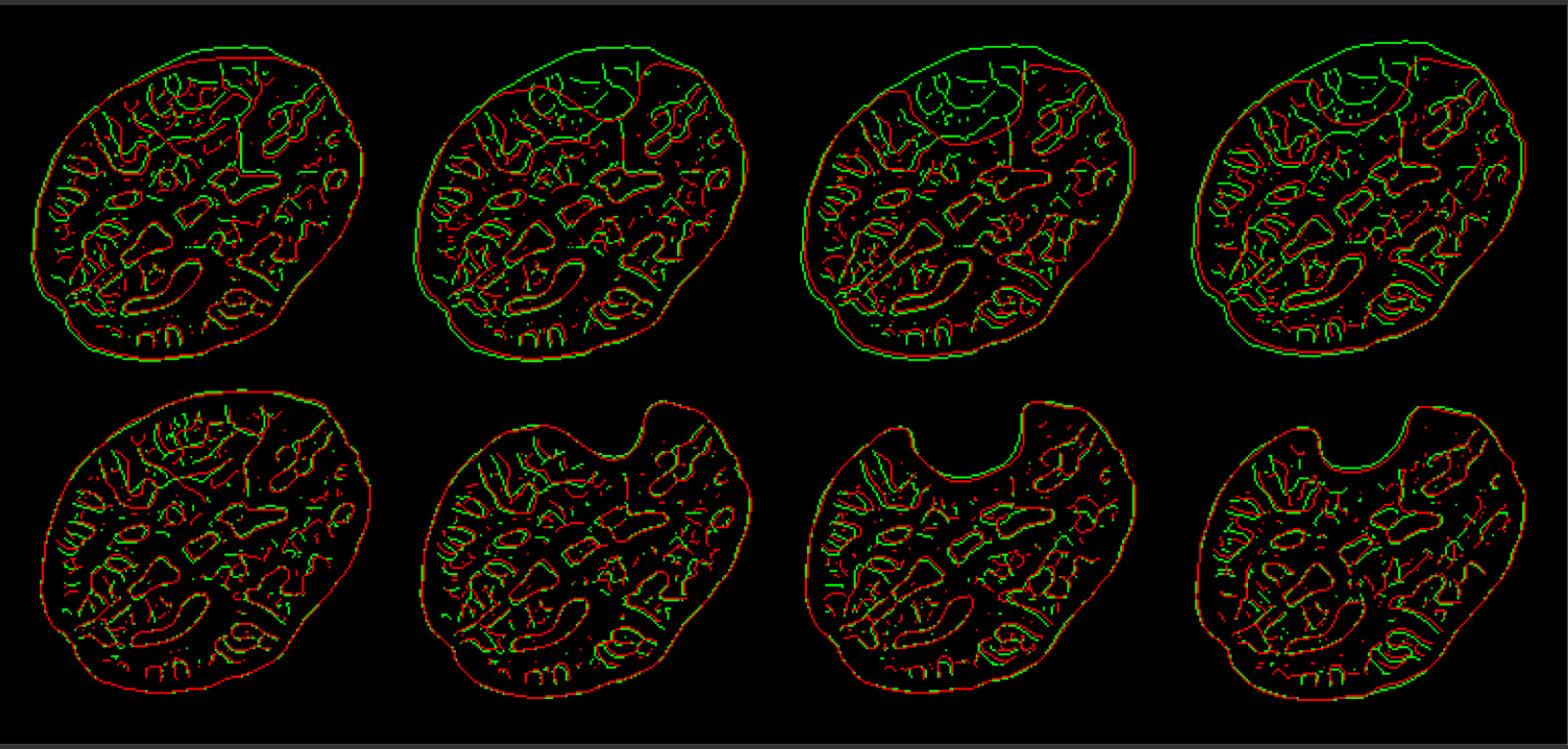



Resection incomplete



XFEM-based
2nd resection modeling

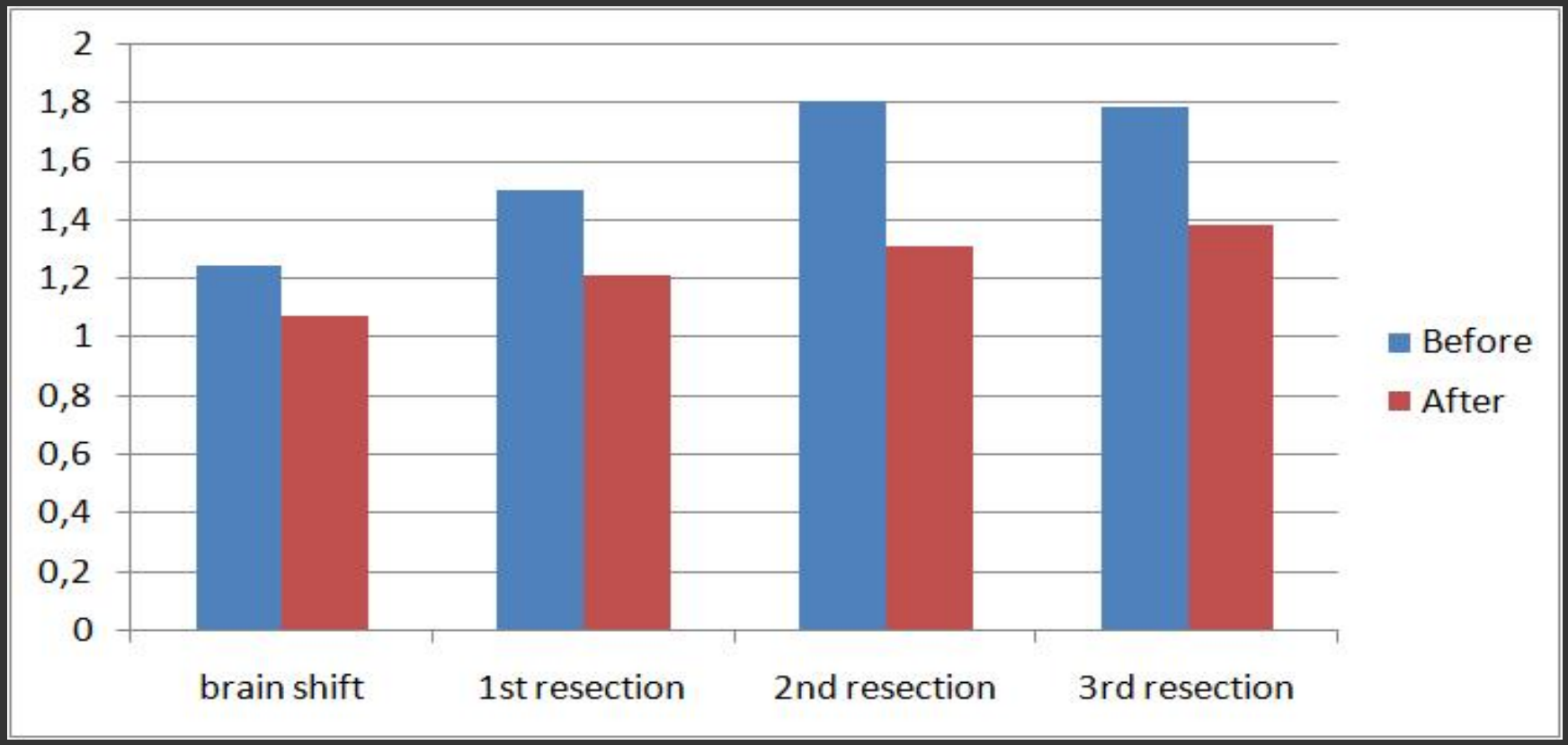
Qualitative validation on Canny edges



Vigneron et al., to be submitted to IEEE TMI

Quantitative validation on Canny edges

Modified Hausdorff distance

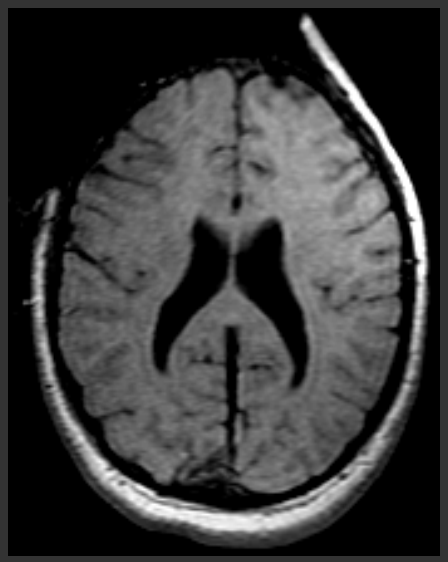


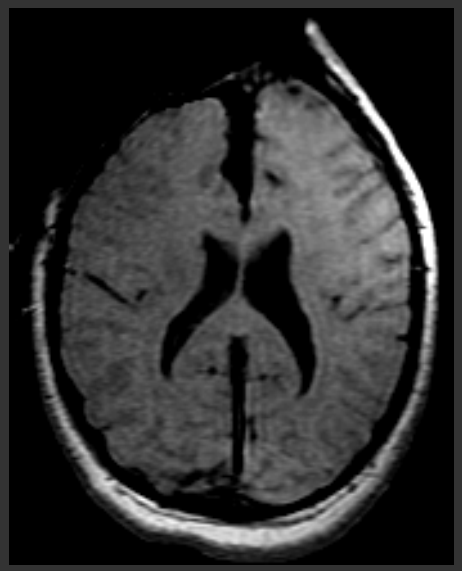
Vigneron et al., to be submitted to IEEE TMI

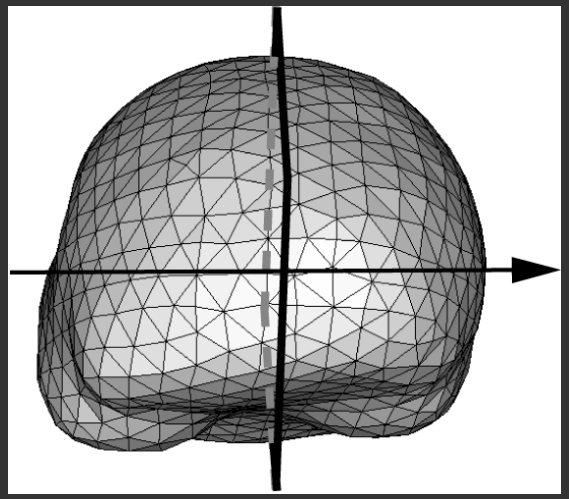
Outline

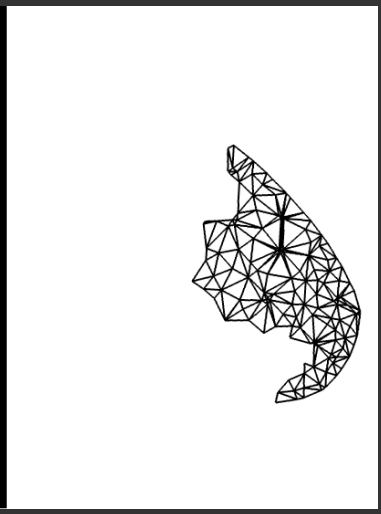
- Developed framework for nonrigid registration
- Basic principles of XFEM
- Modeling of brain shift
- Modeling of successive resections
- Modeling of retraction
- Conclusions and perspectives

Cut is defined using the segmented images

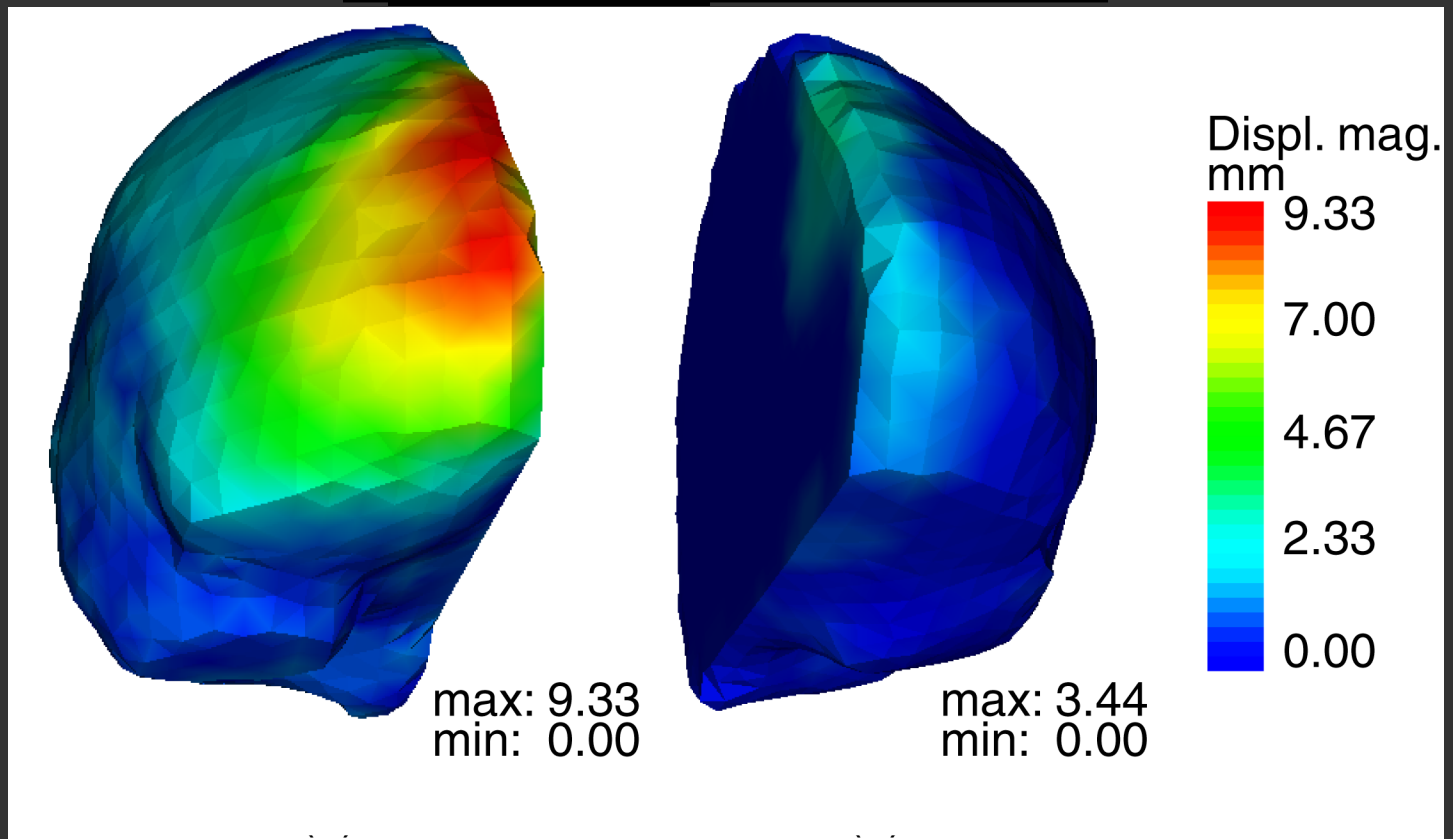




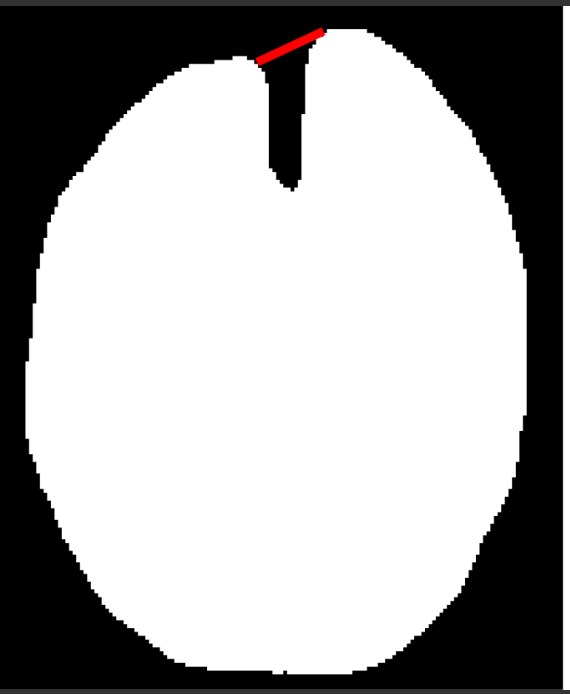


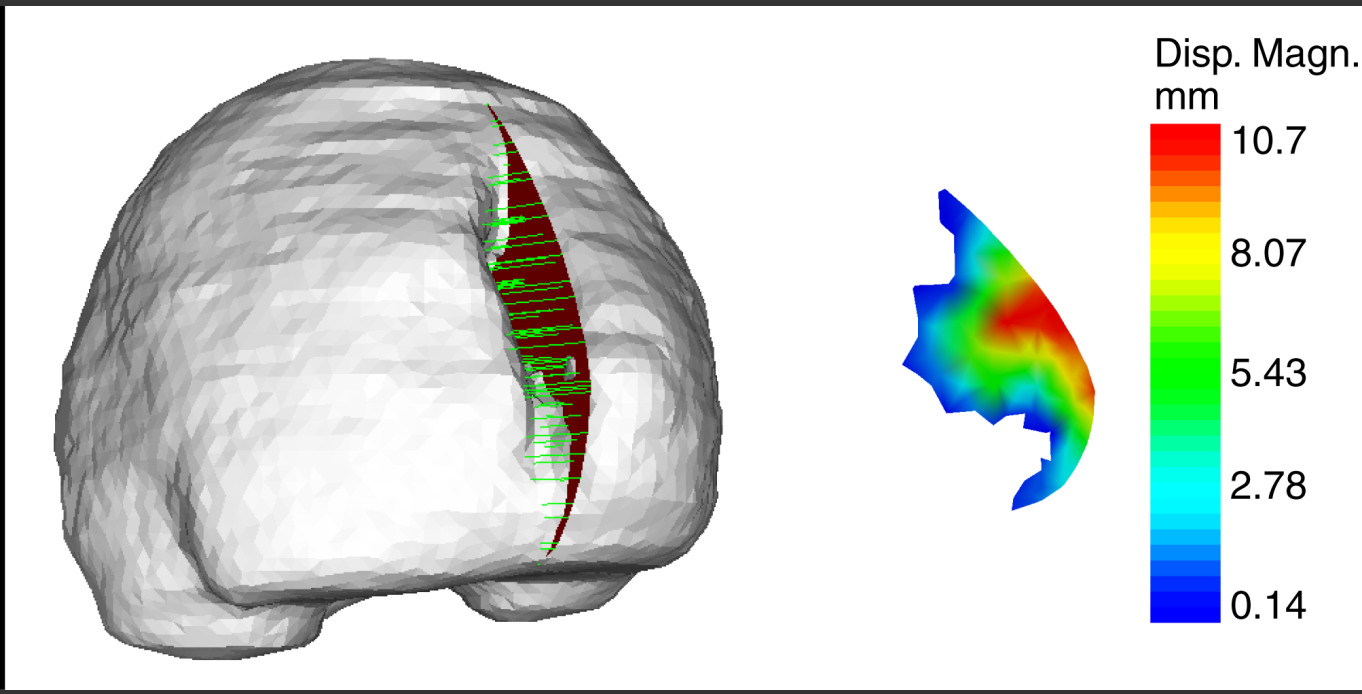


External surface displacement field is decoupled between two brain hemispheres



Cut lips are also used as surface landmarks





XFEM-based biomechanical volume deformation for retraction modeling

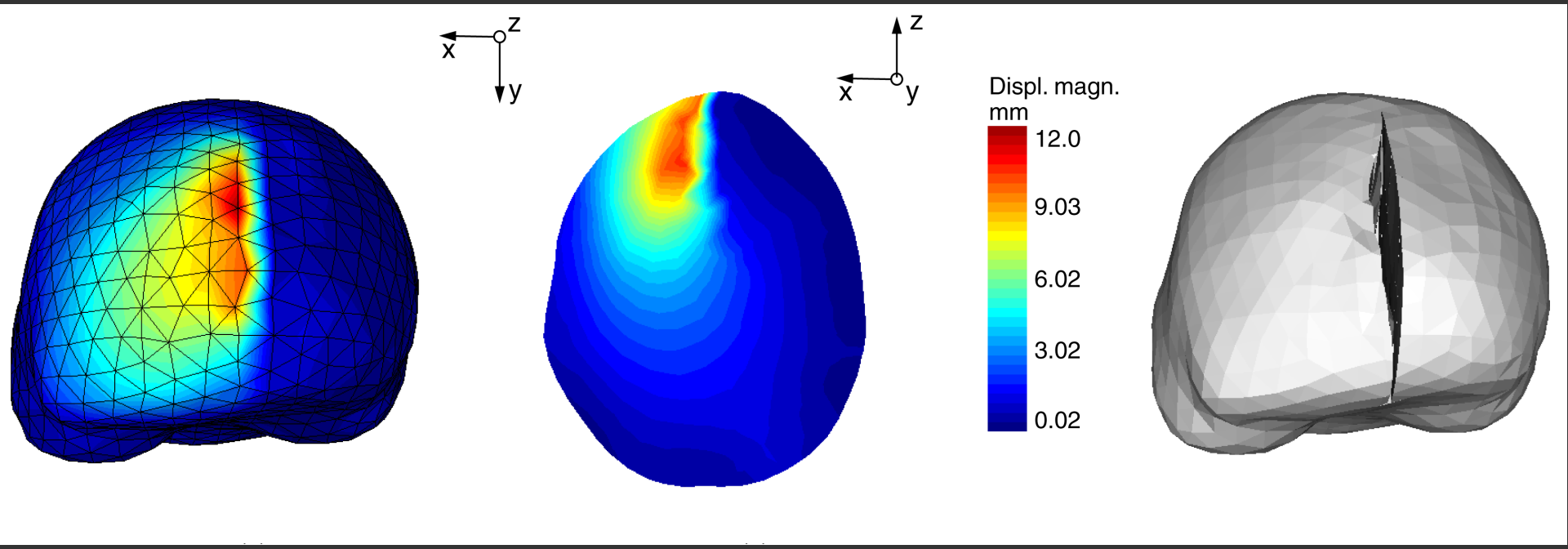
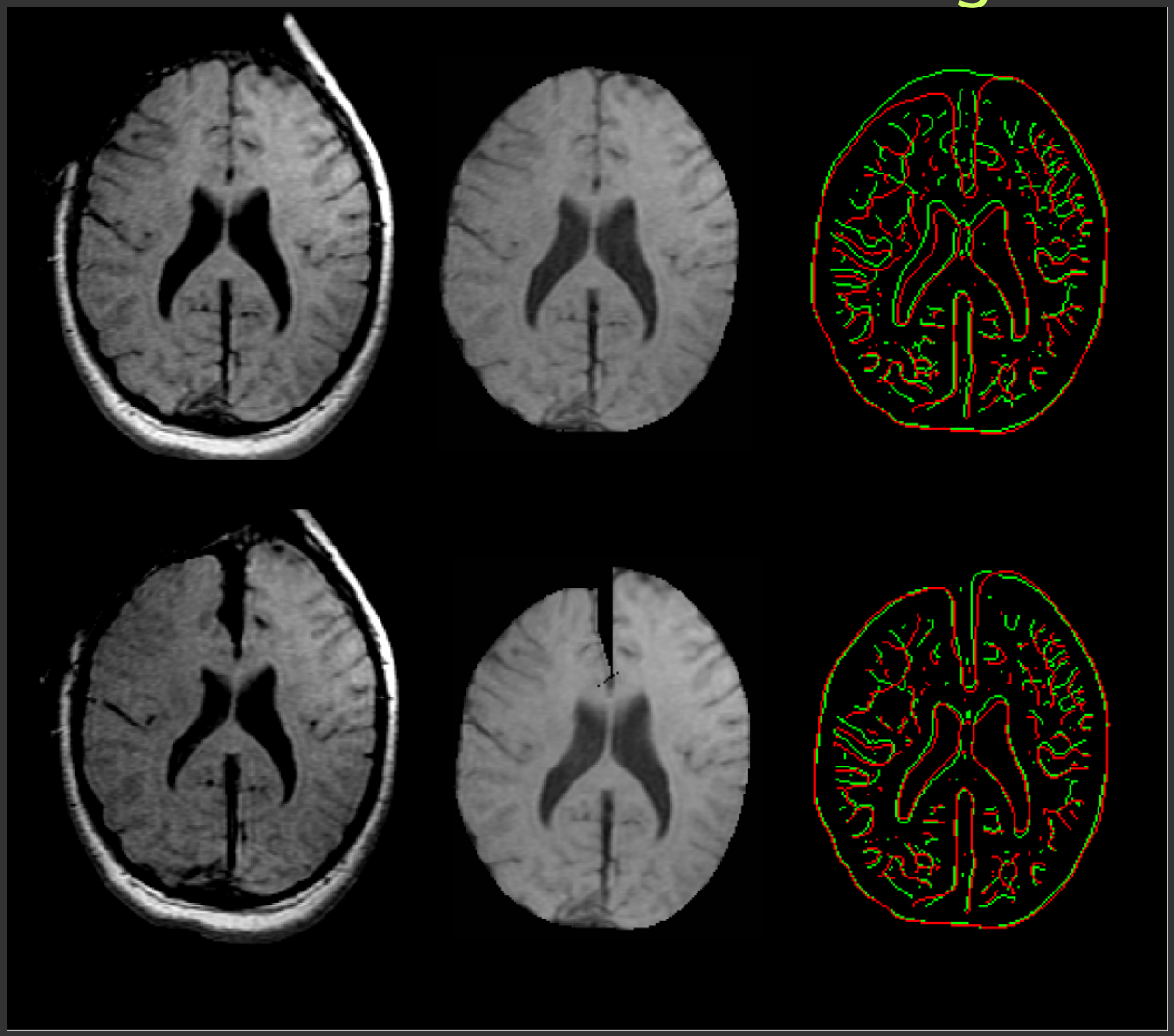


Image update and validation for retraction modeling



Modified Hausdorff Distance: 1.36 mm->1.10 mm

Vigneron et al., to be submitted to Journal of Biomechanics

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Key contributions
for improvement of IGNS sytems

- Design of a global framework for serial preoperative image update
- Developement of this global framework in linear formulation
- Original application of XFEM in IGNS
- Critical study of the methods implemented
- Validation on several patient cases

Perspectives for practical use in the operating room

- Real-time processing (automatic segmentation)
- Modeling retraction followed by resection
- Tracking additional landmarks
- Improving the active surface algorithm
- Using Ultrasound and PoleStar images

Thank you
for your attention!