Electrical field modeling

Institute for Biomagnetism and Biosignalanalysis

Westfälische Wilhelms-Universität Münster

Carsten H. Wolters

16th Practical Course in TES and TMS, Göttingen, Feb. 12, 2019

Outline

- Literature
- Head model generation: MRI/DTI registration and segmentation and individual modeling of head tissue conductivities
- Forward problems in EEG/MEG and TES/TMS: Helmholtz reciprocity, validation work
- Target reconstruction: Combined EEG/MEG source analysis
- Inverse problem: Optimization approaches for multi-sensor tES/TMS and application to the individual stimulation of the somatosensory cortex
- Summary

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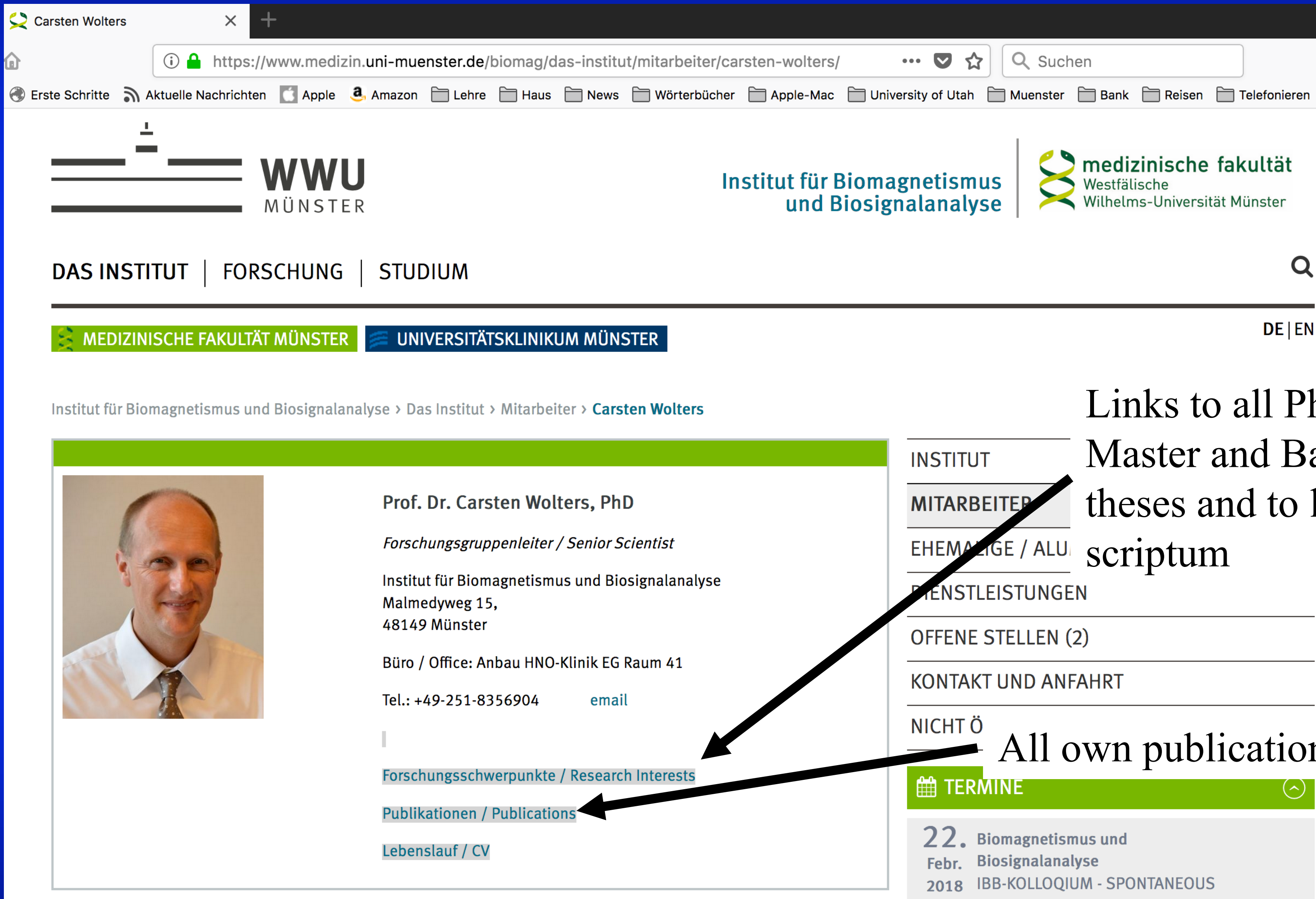
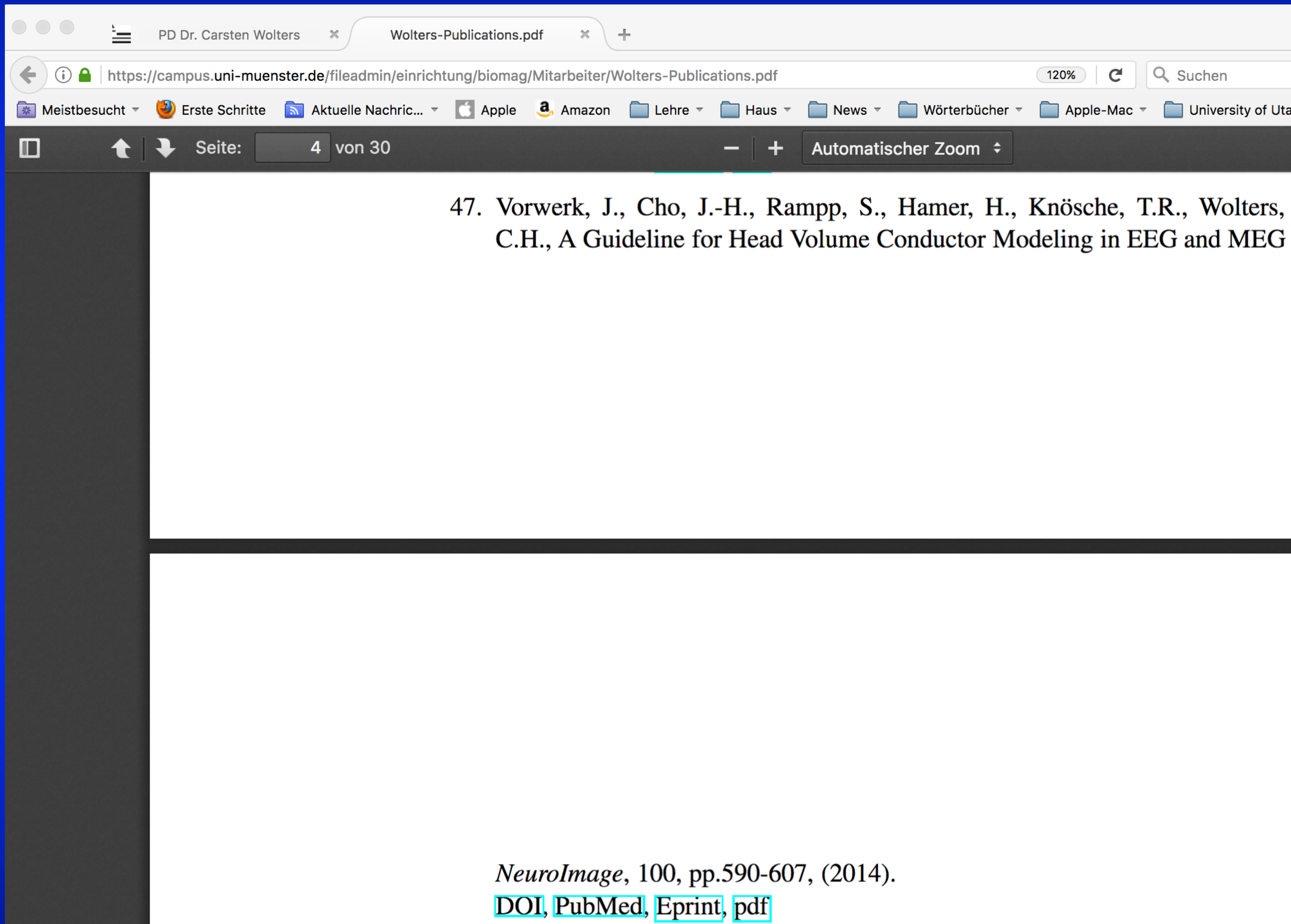
Link for literature to own work:



Links to all PhD, Master and Bachelor theses and to lecture scriptum

All own publications

Link for literature to own work:



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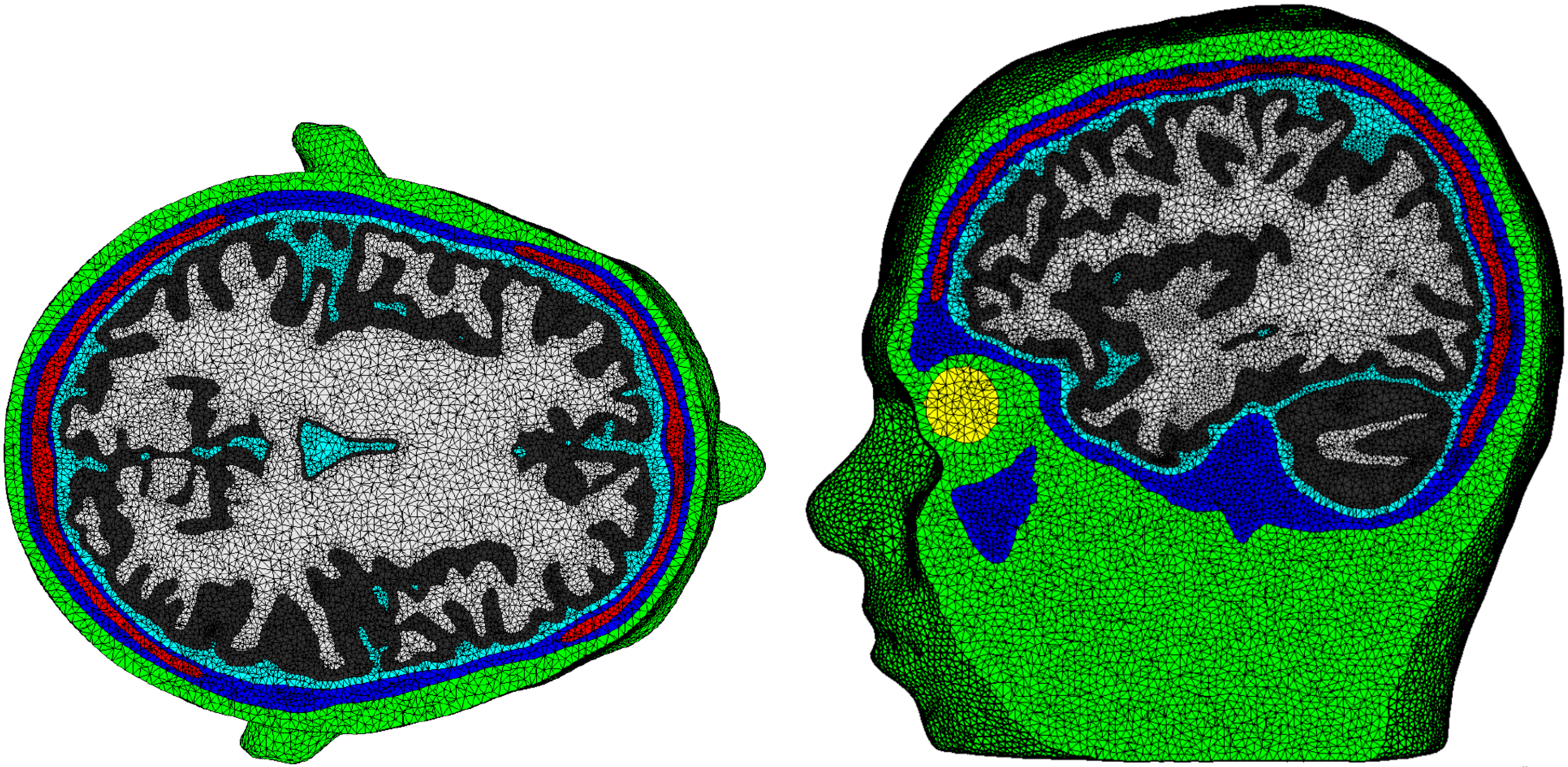
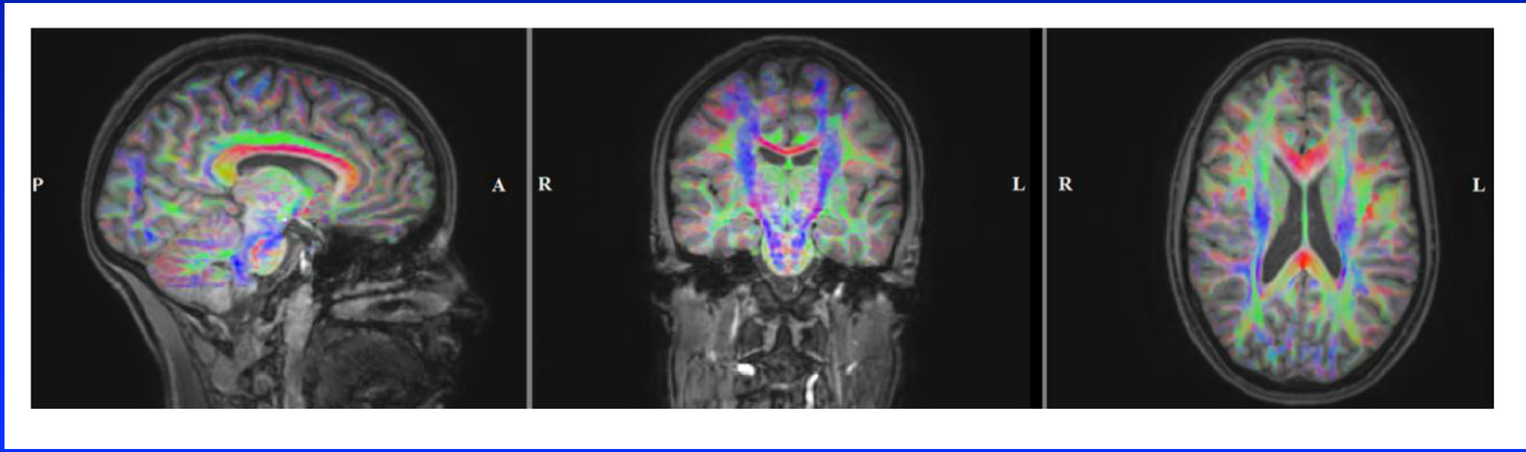
[Vorwerk, Cho, Rampp, Hamer, Knösche & Wolters, *NeuroImage*, 2014]

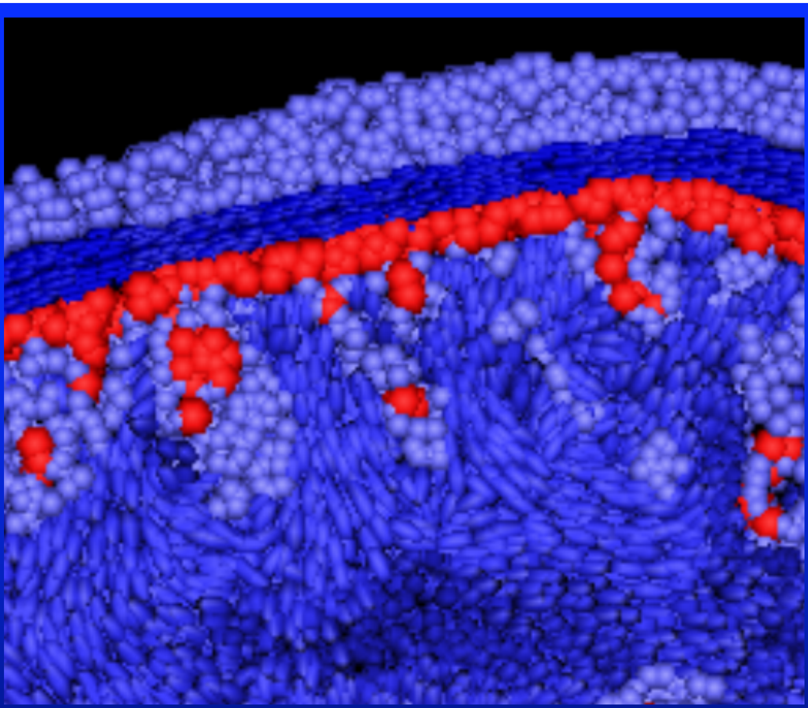
Goal: Calibrated realistic finite element method (FEM) head volume conductor model…



[Vorwerk, Cho, Rampp, Hamer, Knösche & Wolters, *NeuroImage*, 2014]
[Wolters, Anwander, Tricoche, Weinstein, Koch & MacLeod, *NeuroImage*, 2006]

…with white matter conductivity anisotropy





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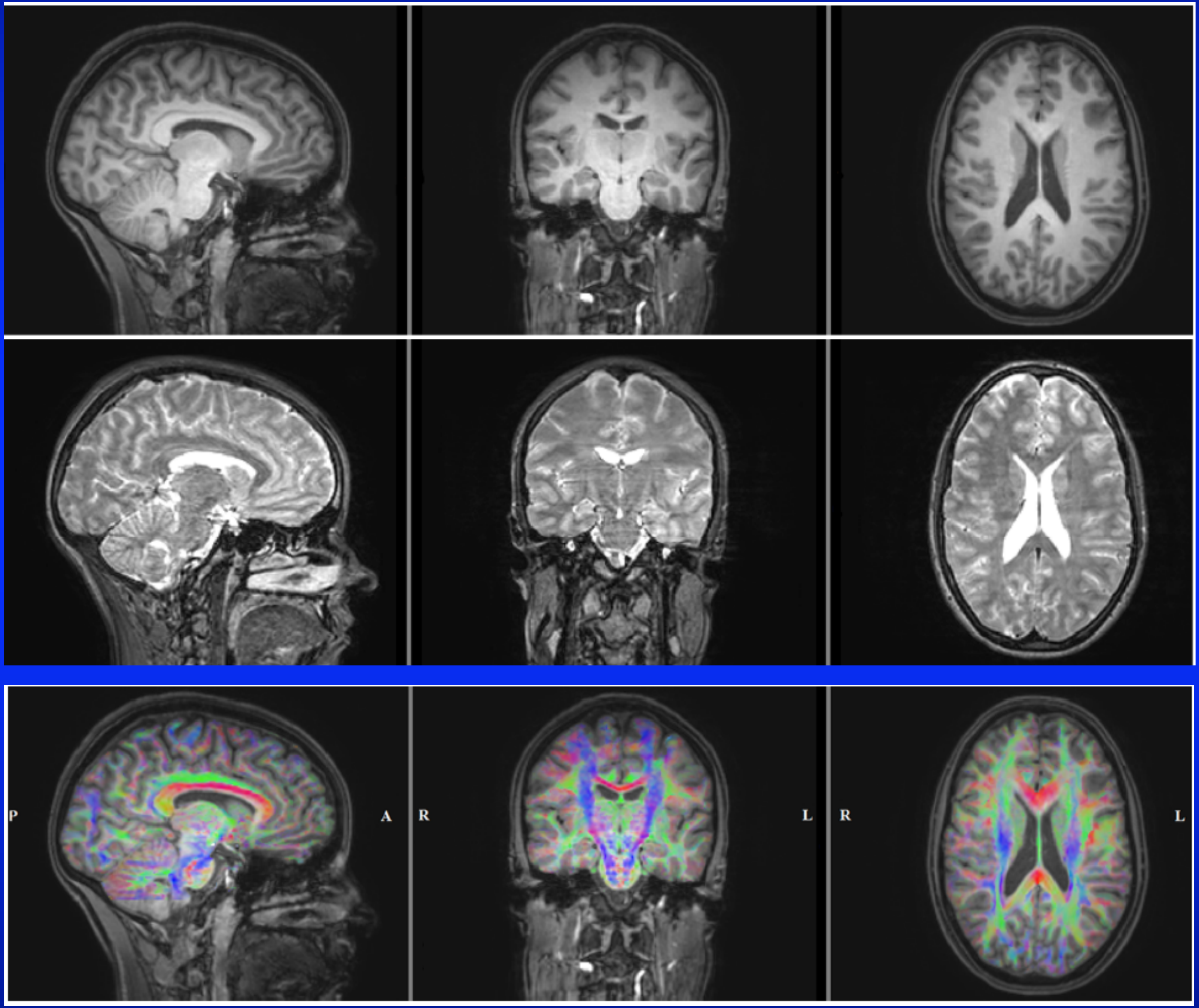
[Aydin, Vorwerk, Küpper, Heers, Kugel, Galka, Hamid, Wellmer, Kellinghaus, Rampp & Wolters, *Plos One*, 2014]

Recommended input: MRI data (27 min measurement time)



T1w-MRI

T2w-MRI

Dw-MRI

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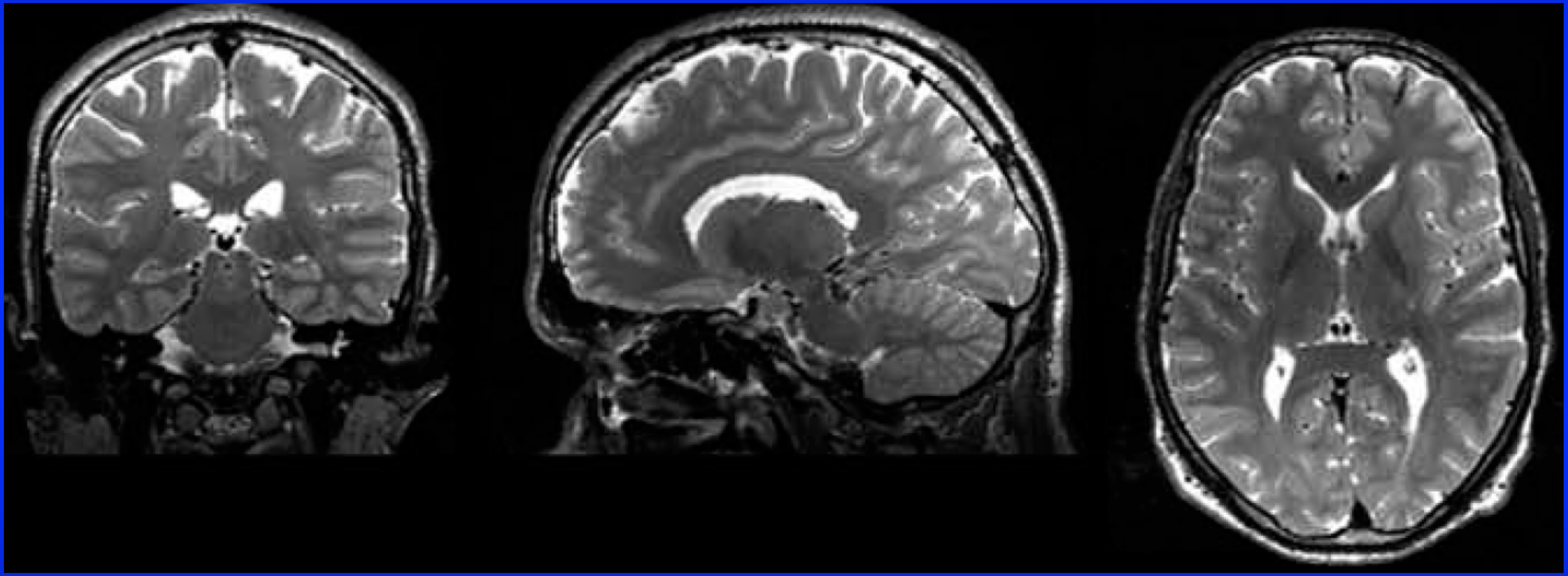
[Vorwerk, Cho, Rampp, Hamer, Knösche & Wolters, *NeuroImage*, 2014]
[Aydin, Vorwerk, Küpper, Heers, Kugel, Galka, Hamid, Wellmer, Kellinghaus, Rampp & Wolters, *Plos One*, 2014]

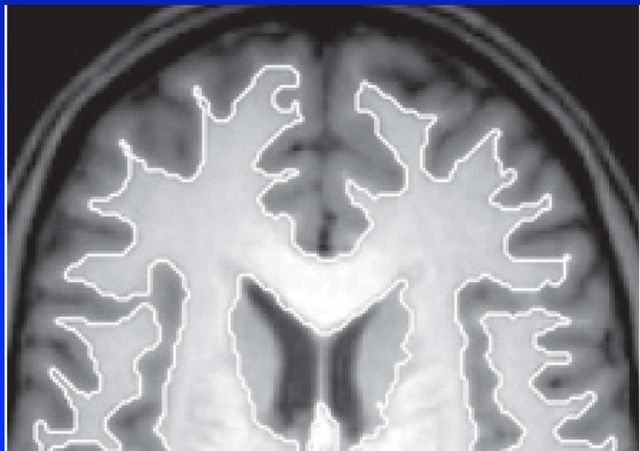
Why T2-MRI: Good basis for segmentation of CSF and skull



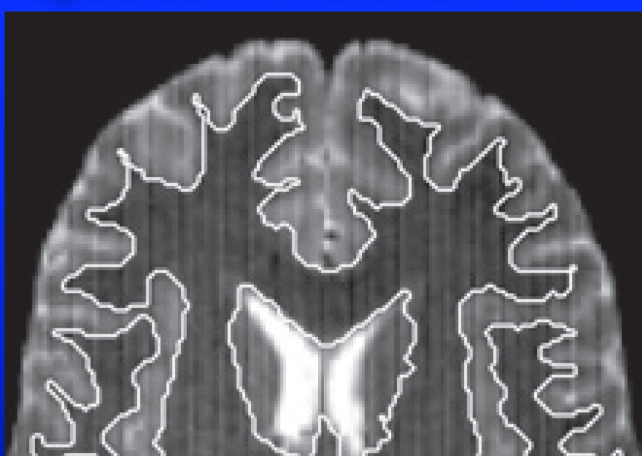
Registration of multimodal MRI for head volume conductor modeling

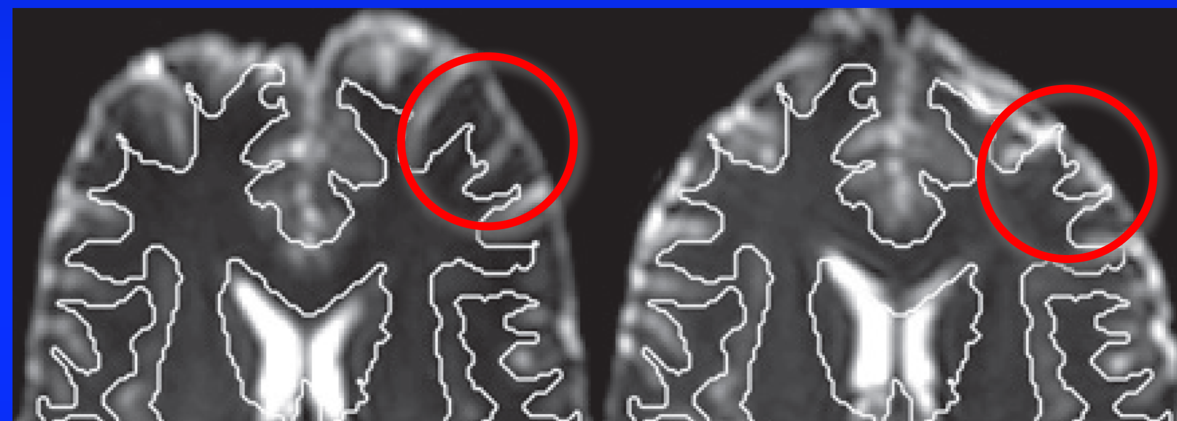
[Ruthotto, Kugel, Olesch, Fischer, Modersitzki, Burger & Wolters, *Phys Med Biol*, 2012]

Registration of T1w-, T2w- and dw-MRI



White matter surface on linearly registered T1w- and T2w-MRI





I_1 I_2

Not good enough: White matter surface on linearly registered DW-MRI with flat diffusion gradients (diffusion weighting factor b=0) and reversed spatial (i.e., phase and frequency) encoding gradients ($\mathbf{I_1}$ and $\mathbf{I_2}$)

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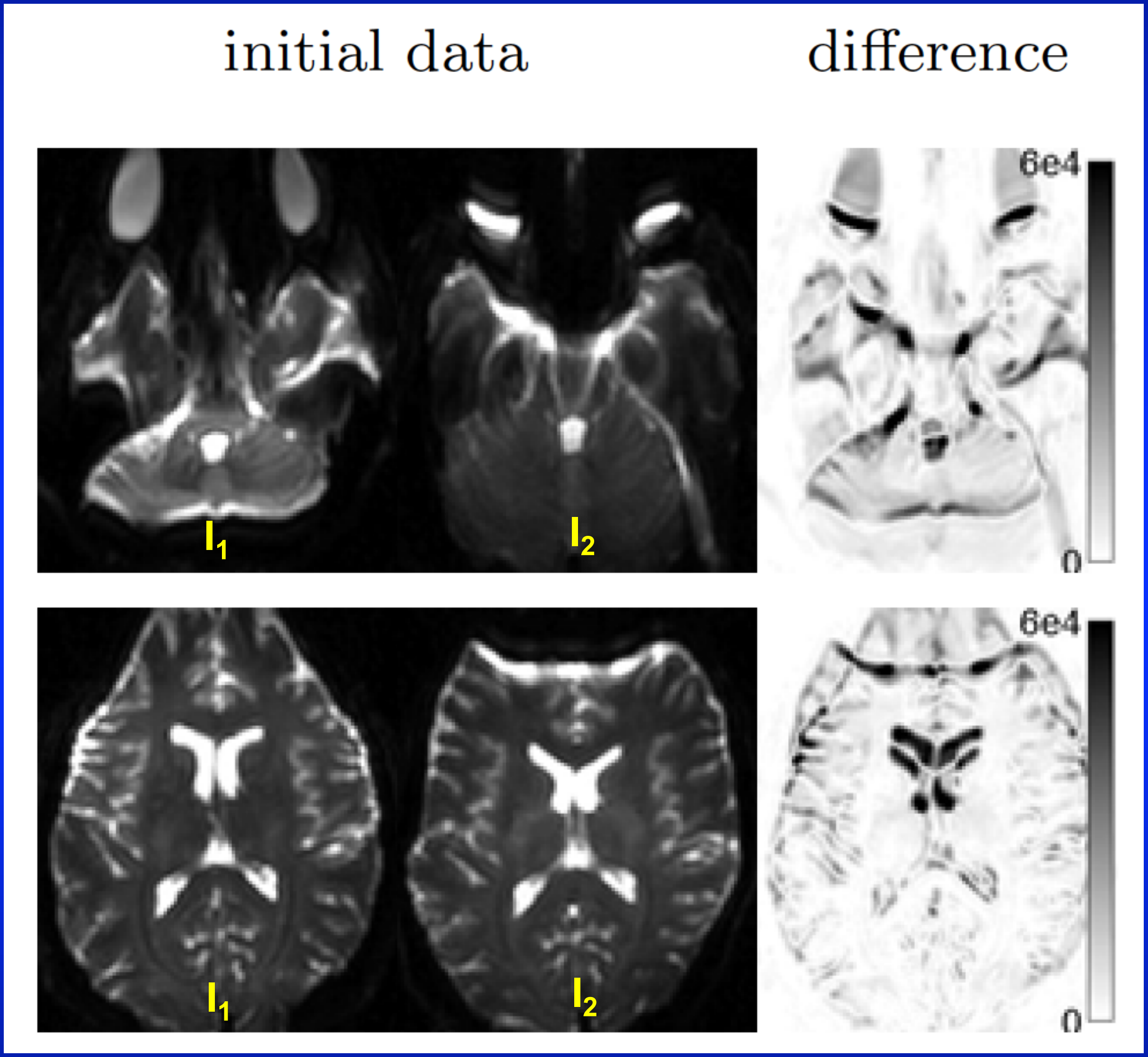
[Ruthotto, Kugel, Olesch, Fischer, Modersitzki, Burger & Wolters, *Phys Med Biol*, 2012]

Nonlinear registration and correction of dw-MRI



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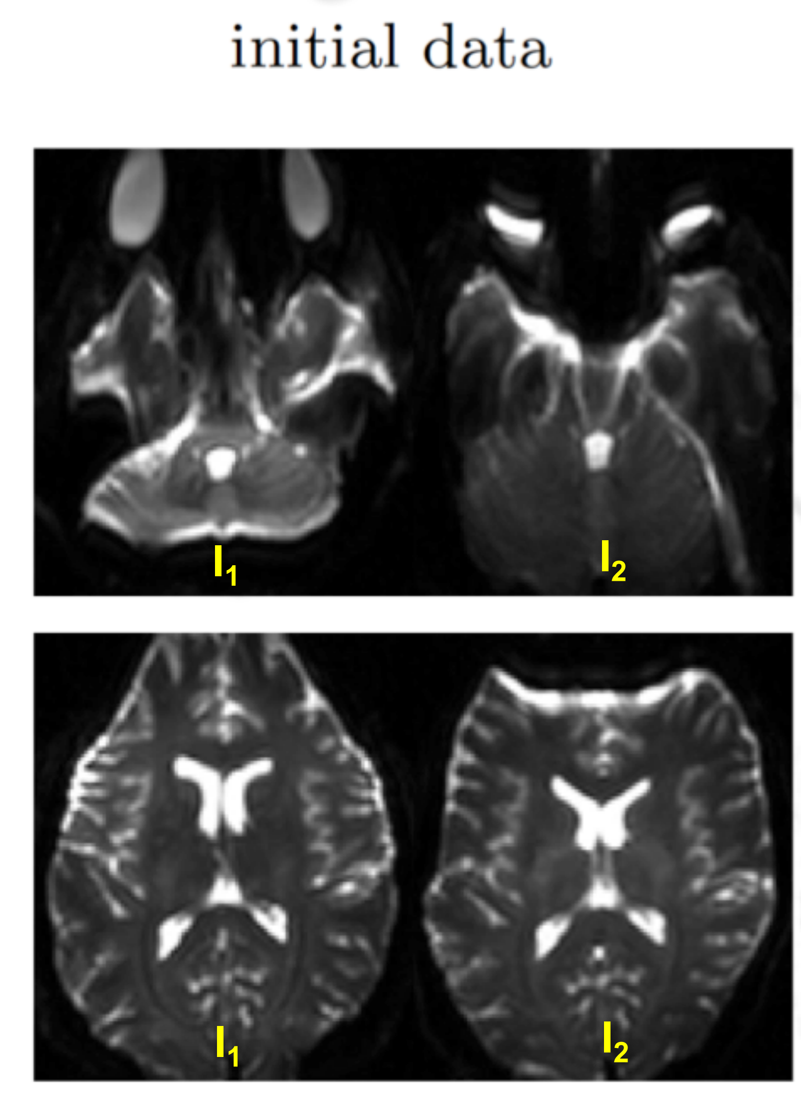
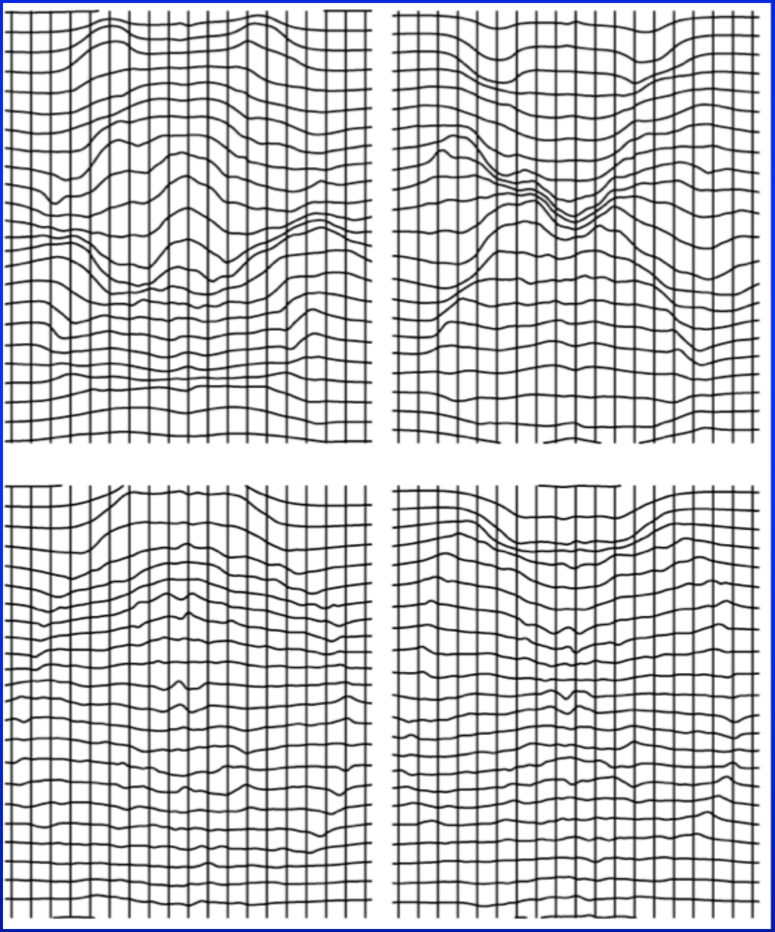
[Ruthotto, Kugel, Olesch, Fischer, Modersitzki, Burger & Wolters, *Phys Med Biol*, 2012]

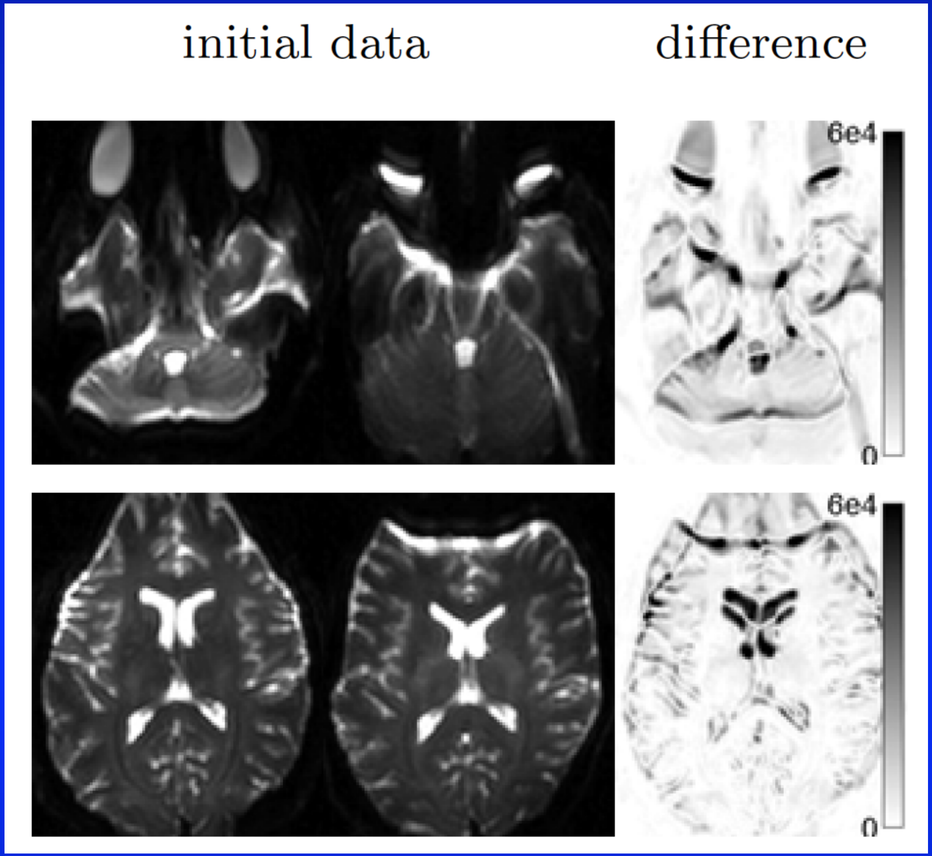
Compute nonlinear diffeomorphic mass-preserving registration and apply it to a regular grid

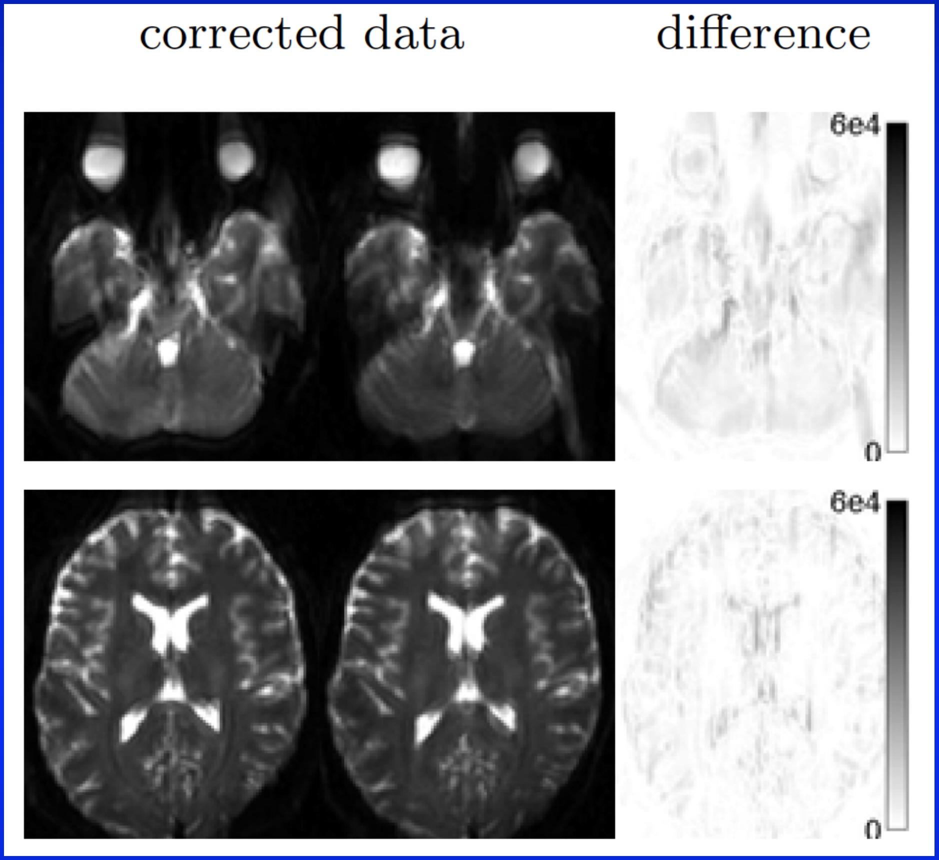




[Ruthotto, Kugel, Olesch, Fischer, Modersitzki, Burger & Wolters, *Phys Med Biol*, 2012]

Apply registration to initial data for correction





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[Ruthotto, Kugel, Olesch, Fischer, Modersitzki, Burger & Wolters, *Phys Med Biol*, 2012]
[Aydin, Vorwerk, Küpper, Heers, Kugel, Galka, Hamid, Wellmer, Kellinghaus, Rampp & Wolters, *Plos One*, 2014]

Software for registration of multimodal MRI for head volume conductor modeling:

- Open source SPM HySCO registration tool

  (http://www.diffusiontools.com/documentation/hysco.html)

Segmentation of multimodal MRI for head volume conductor modeling

[Lanfer, Paul-Jordanov, Scherg, Wolters, *HBM*, 2013]
[Lanfer, *PhD thesis in Mathematics*, WWU Münster, 2014]

Automatic head tissue segmentation from T1- and T2-MRI

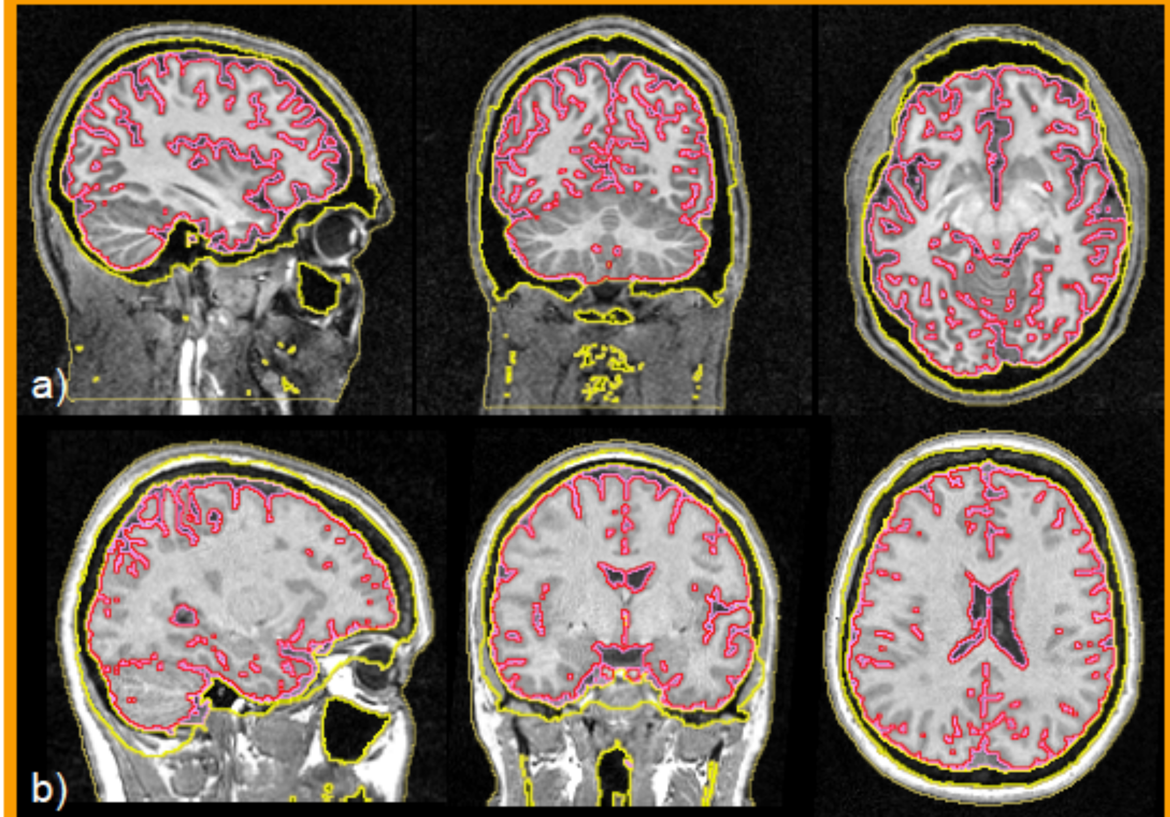

Fig. 3
Tissue outlines of segmentation results based on a) T1- and T2-MRI, and b) on T1-MRI only overlaid onto orthogonal slices of T1-MRI. Results were relabeled from eight to four tissues (see legend) for a clearer presentation.

- Scalp (muscle/scalp and subcutaneous tissue)
- Skull (compact and cancellous bone)
- CSF (CSF and dura mater)
- Brain (GM and WM)

- Skin, skull, CSF and brain surfaces reconstructed from T1- and T2-MRI (Fig.3a) and only from T1-MRI (Fig.3b)
- Accurate and quasi-automatic segmentation of major head tissue compartments
- Accurate skull segmentation is especially important for applications in bioelectromagnetism

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Software for segmentation of multimodal MRI for head volume conductor modeling:

- Open source SPM12 toolbox for multi-compartment segmentation: http://www.fil.ion.ucl.ac.uk/spm/software/spm12
- Open source Seg3D toolbox: Compacta and spongiosa segmentation and manual correction: http://www.sci.utah.edu/cibc-software/seg3d.html
- Open source Freesurfer toolbox for segmentation of grey matter: http://surfer.nmr.mgh.harvard.edu
- Open source FSL toolbox for segmentation of skin, skull, brain: http://www.fmrib.ox.ac.uk/fsl
- Open source SIMNIBS toolbox: http://simnibs.de/
- Lanfer-dissertation resulted in user-friendly, but commercialized, BESA-MRI pipeline: http://www.besa.de/products/besa-mri/besa-mri-overview/

Head tissue conductivity modeling

Simulation of two patch auditory TES

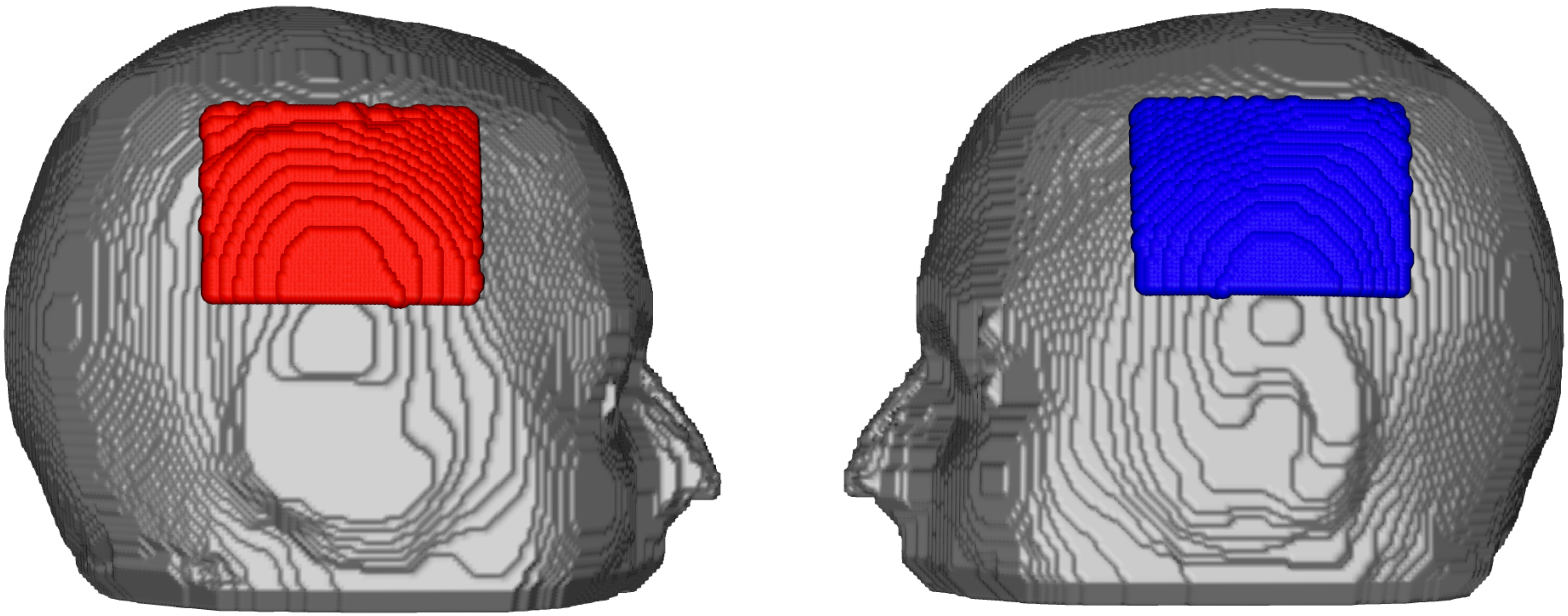

Figure: Two conventional tCS patches are modeled as rectangular sponge-based pads with a commonly used size in clinical practice of 7x5 cm, thickness of 4mm and saline-like conductivity of 1.4 S/m. The anode is colored red and the cathode is blue.

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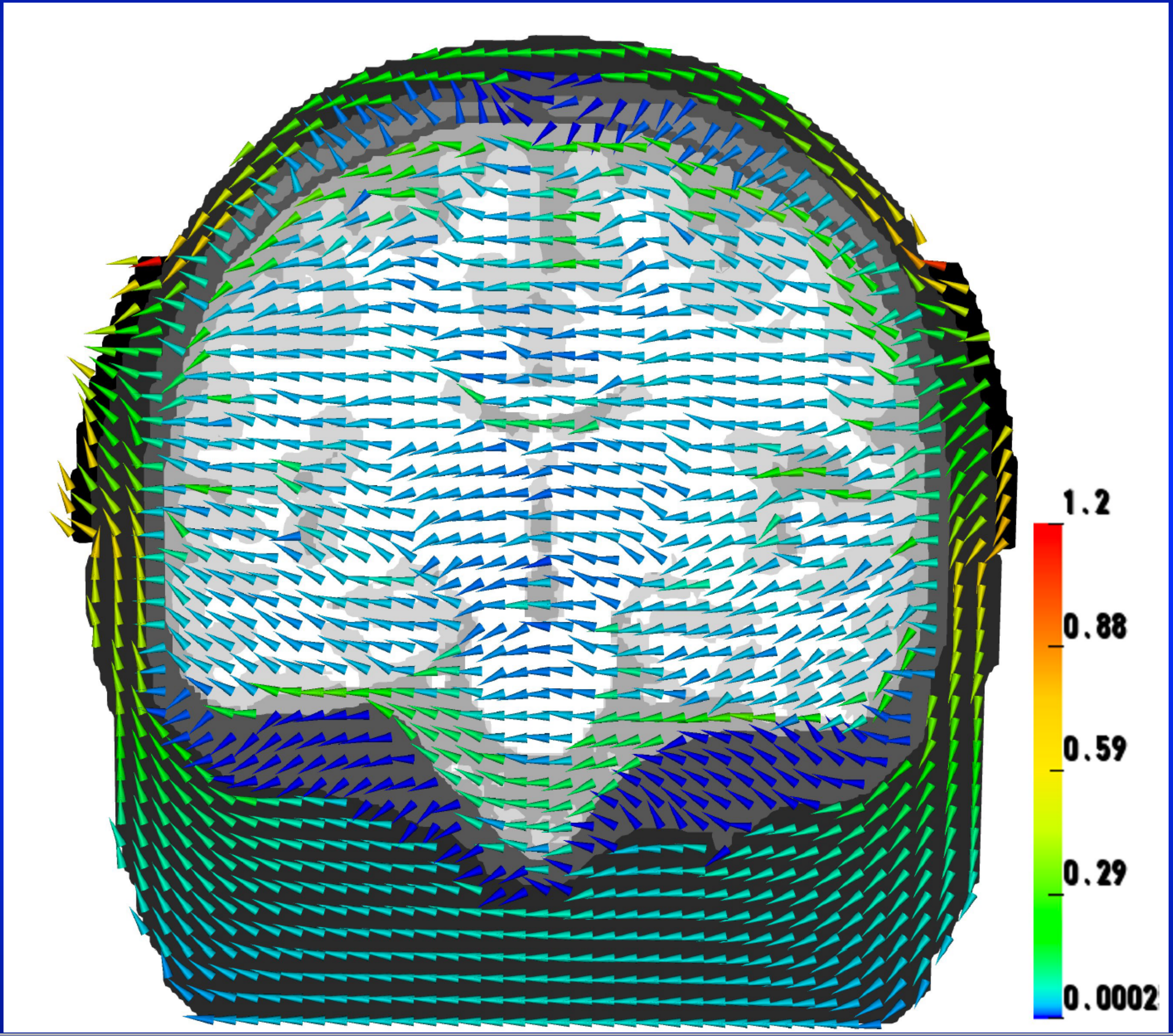
[Wagner, Rampersad, Aydin, Vorwerk, Oostendorp, Neuling, Herrmann, Stegeman & Wolters, *J. Neur. Eng.*, 2014]

Current density in 6 comp. anisotropic head model



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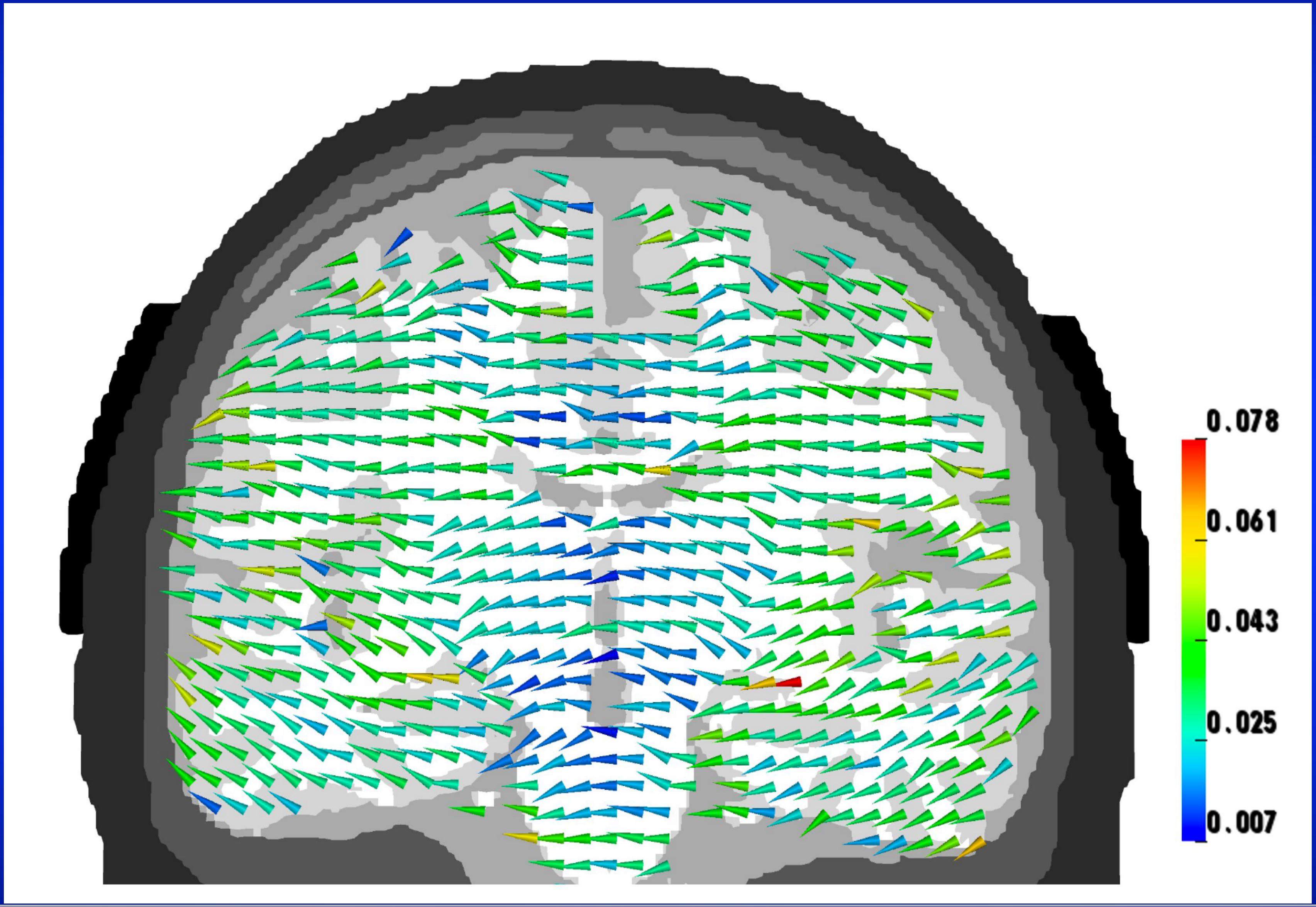
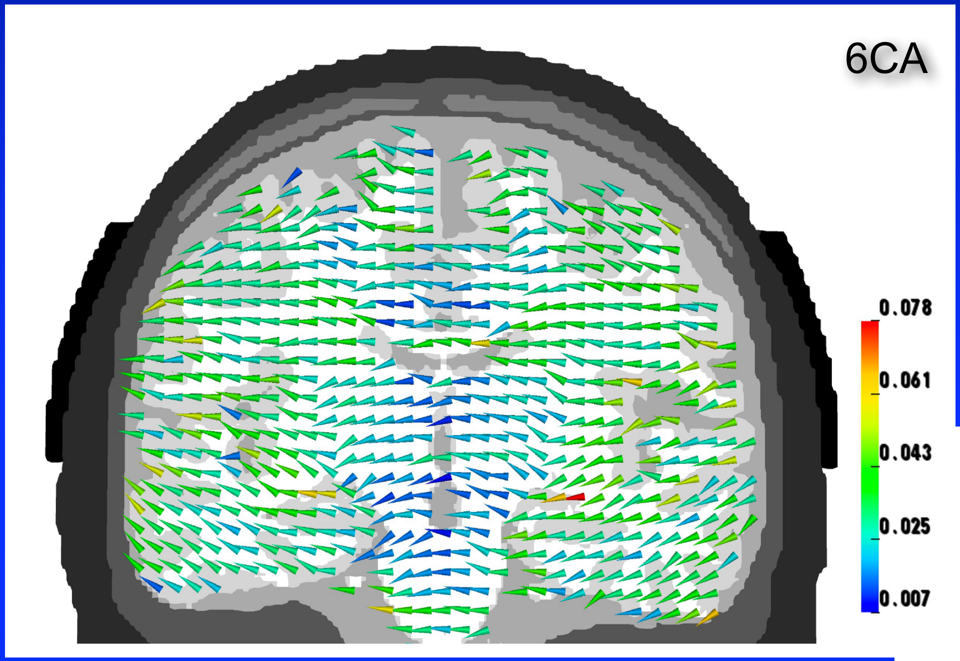
[Wagner, Rampersad, Aydin, Vorwerk, Oostendorp, Neuling, Herrmann, Stegeman & Wolters, *J. Neur. Eng.*, 2014]

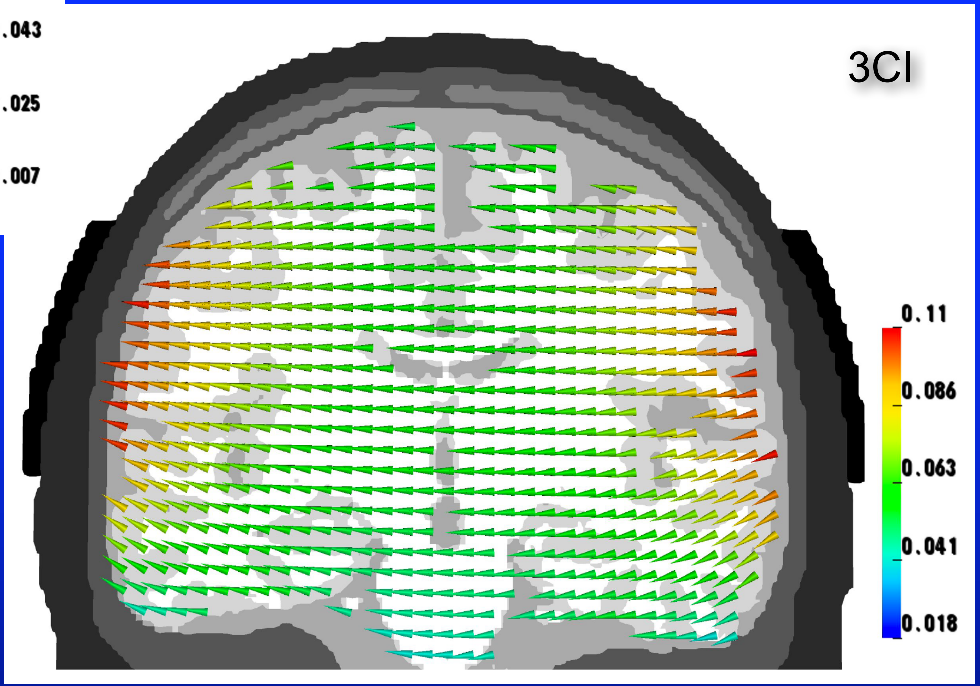
Brain current density in 6 comp. anisotropic head model



[Wagner, Rampersad, Aydin, Vorwerk, Oostendorp, Neuling, Herrmann, Stegeman & Wolters, *J. Neur. Eng.*, 2014]

Comparison: Brain current density in 6 compartment anisotropic (6CA) and in 3 compartment isotropic (3CI) head model





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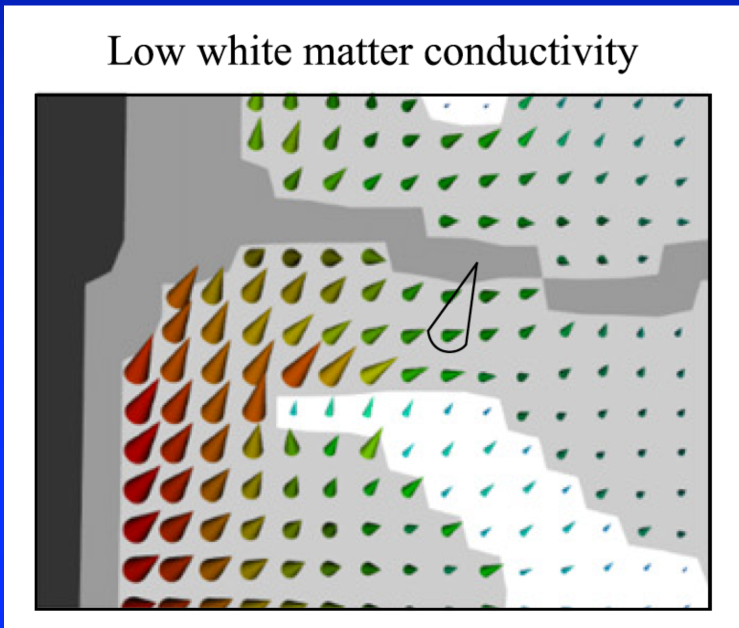
Influence of white matter conductivity



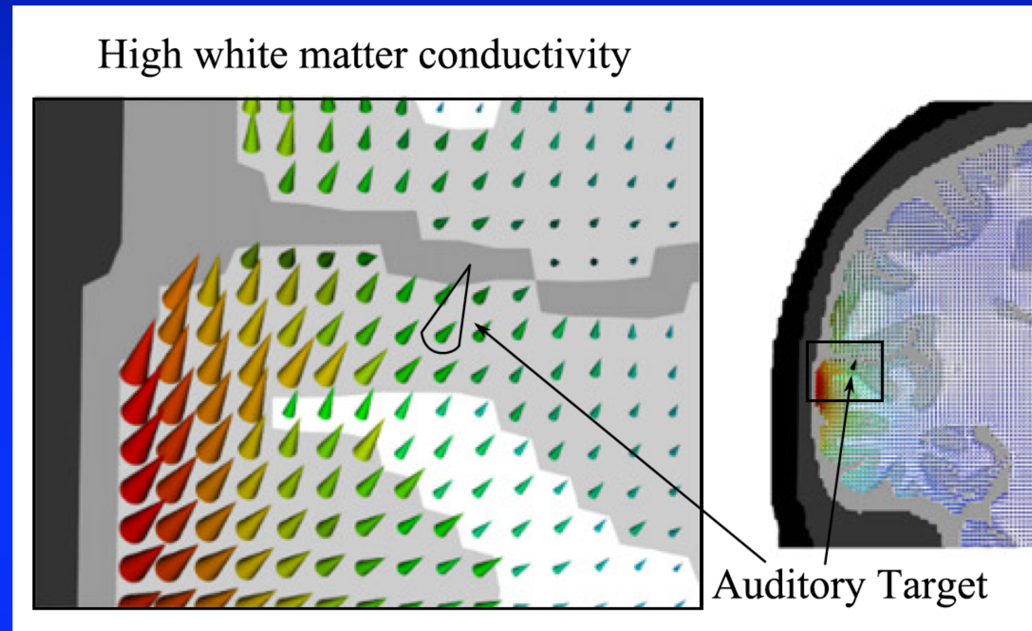


Table 2. Sensitivity of the stimulation amplitudes of the main electrodes with respect to the uncertainty in each tissue type and the stochastic interactions for the conductivity of skin σ_{skin}, skull σ_{sku} gray matter σ_{gm}, and white matter σ_{wm}.

	Sensitivity on stimulation amplitude		
Parameter	T8(%)	FC6(%)	FT8(%)
σ_{skin}	5.9	7.7	4.0
σ_{skull}	**28.9**	**79.8**	**70.1**
σ_{gm}	16.2	6.9	13.0
σ_{wm}	**27.2**	0.5	3.1
$\sigma_{\text{skin}}, \sigma_{\text{skull}}$	12.0	3.5	6.6
$\sigma_{\text{skull}}, \sigma_{\text{gm}}$	7.3	1.2	2.8
Σ	**97.5**	**99.5**	**99.6**

Influence of skull conductivity

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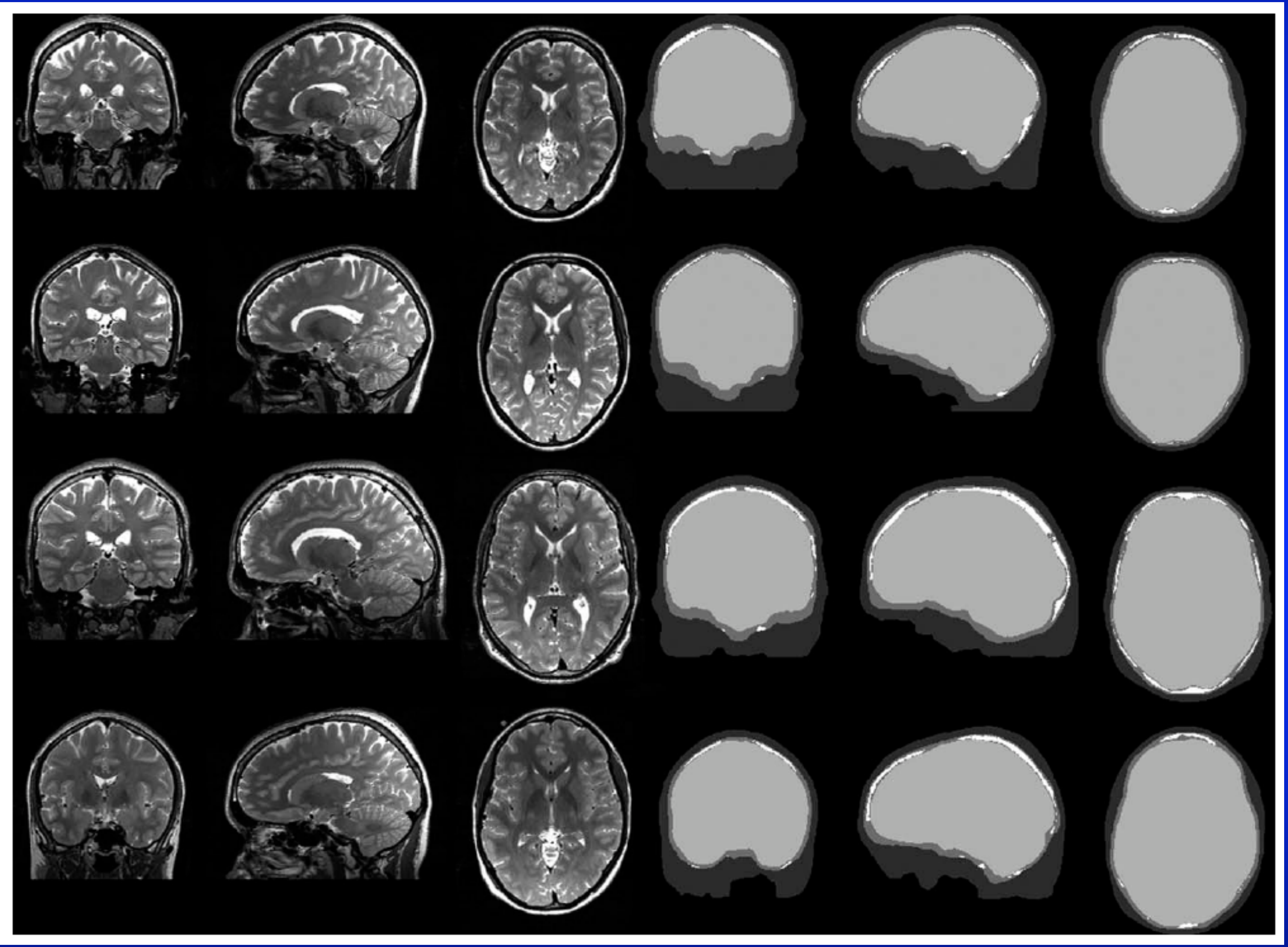
Σ	**97.5**	**99.5**	**99.6**

[Dannhauer, Lanfer, Wolters & Knösche, *Human Brain Mapping*, 2011]

Modeling skull compacta and spongiosa



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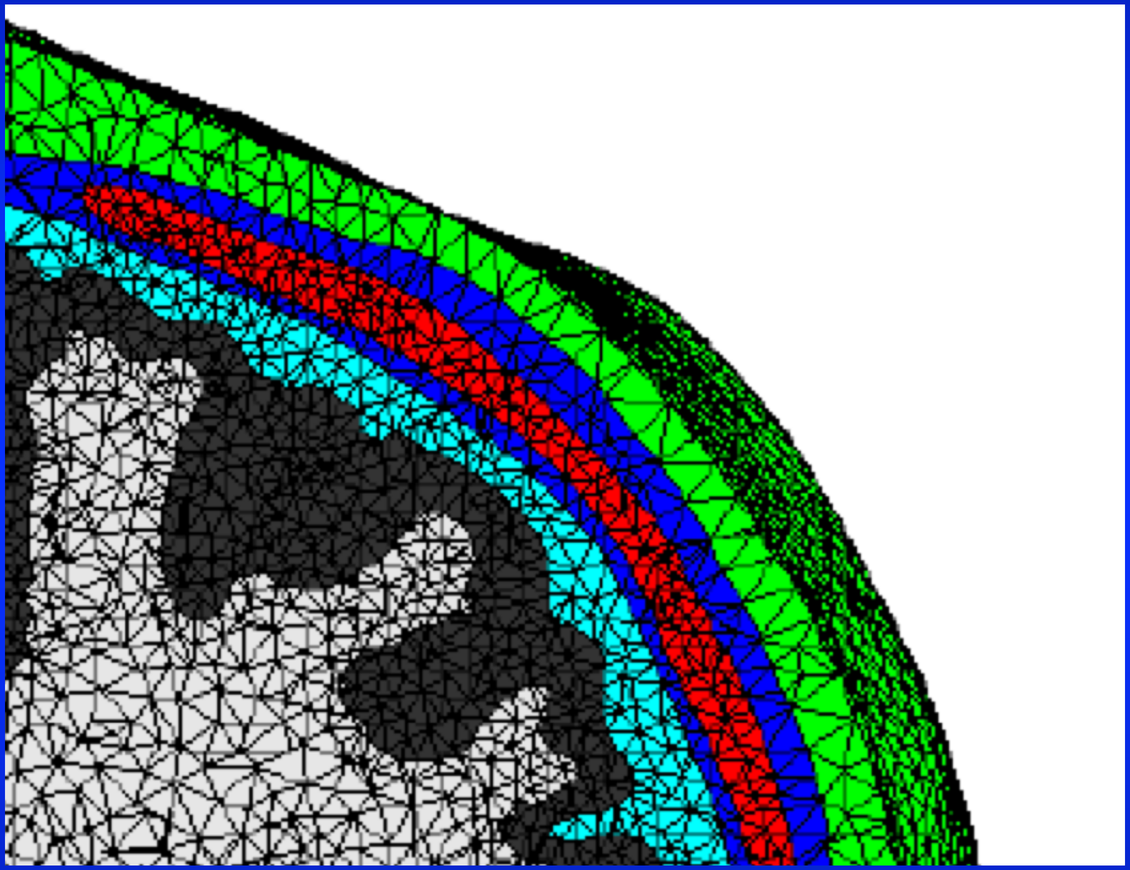
[Lew/Wolters, Anwander, Makeig & MacLeod, *Human Brain Mapping*, 2009]
[Wolters, Lew, MacLeod & Hämäläinen, *Biomed.Eng.*, 2010]
[Aydin, Vorwerk, Küpper, Heers, Kugel, Galka, Hamid, Wellmer, Kellinghaus, Rampp & Wolters, *Plos One*, 2014]

Individual skull conductivity calibration



Conductivity of the skull varies inter- and intra-individually depending, e.g., on age: Literature skull conductivities range from 0.0016 S/m to 0.033 S/m

[Lew, Wolters, Anwander, Makeig & MacLeod, *Human Brain Mapping*, 2009]
[Wolters, Lew, MacLeod & Hämäläinen, *Biomed.Eng.*, 2010]
[Aydin, Vorwerk, Küpper, Heers, Kugel, Galka, Hamid, Wellmer, Kellinghaus, Rampp & Wolters, *Plos One*, 2014]

Individual skull conductivity calibration

Measure somatosensory evoked field (SEF) and potential (SEP) for electrically stimulated median-nerve (7 min)

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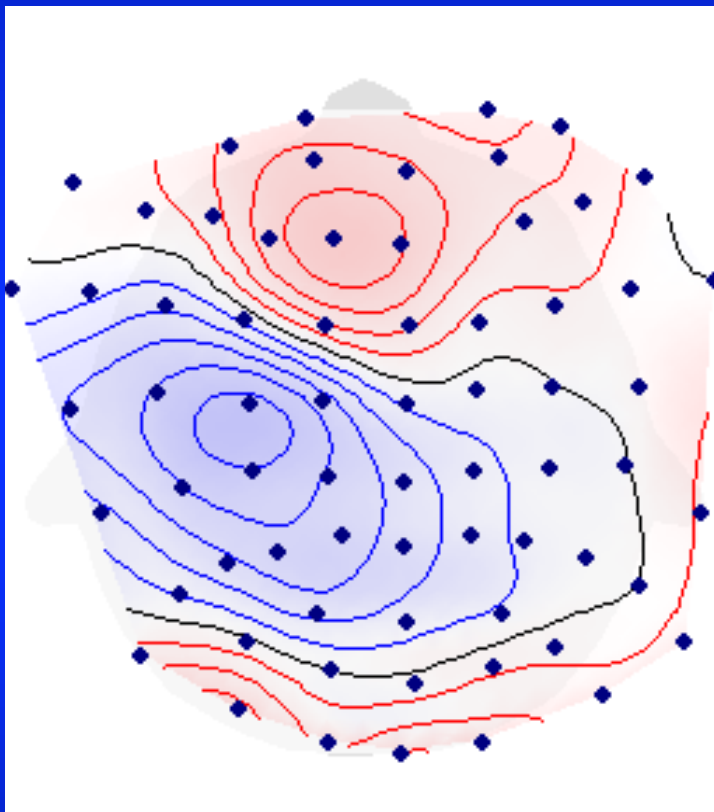
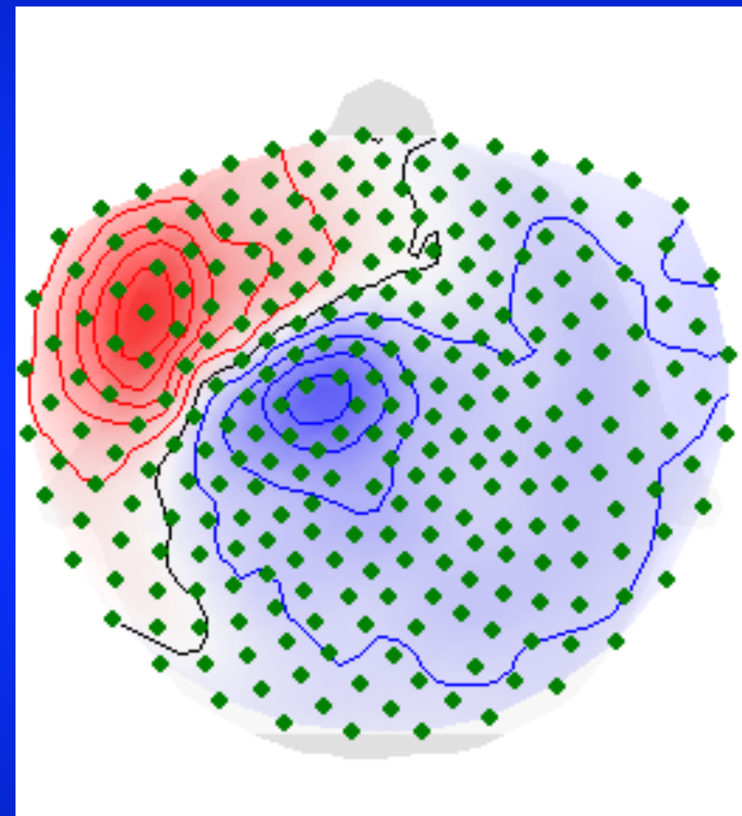
[Lew, Wolters, Anwander, Makeig & MacLeod, *Human Brain Mapping*, 2009]
[Wolters, Lew, MacLeod & Hämäläinen, *Biomed.Eng.*, 2010]
[Aydin, Vorwerk, Küpper, Heers, Kugel, Galka, Hamid, Wellmer, Kellinghaus, Rampp & Wolters, *Plos One*, 2014]

Individual skull conductivity calibration



SEP-P20/N20



SEF-M20

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[Lew, Wolters, Anwander, Makeig & MacLeod, *Human Brain Mapping*, 2009]
[Wolters, Lew, MacLeod & Hämäläinen, *Biomed.Eng.*, 2010]
[Aydin, Vorwerk, Küpper, Heers, Kugel, Galka, Hamid, Wellmer, Kellinghaus, Rampp & Wolters, *Plos One*, 2014]

Individual skull conductivity calibration

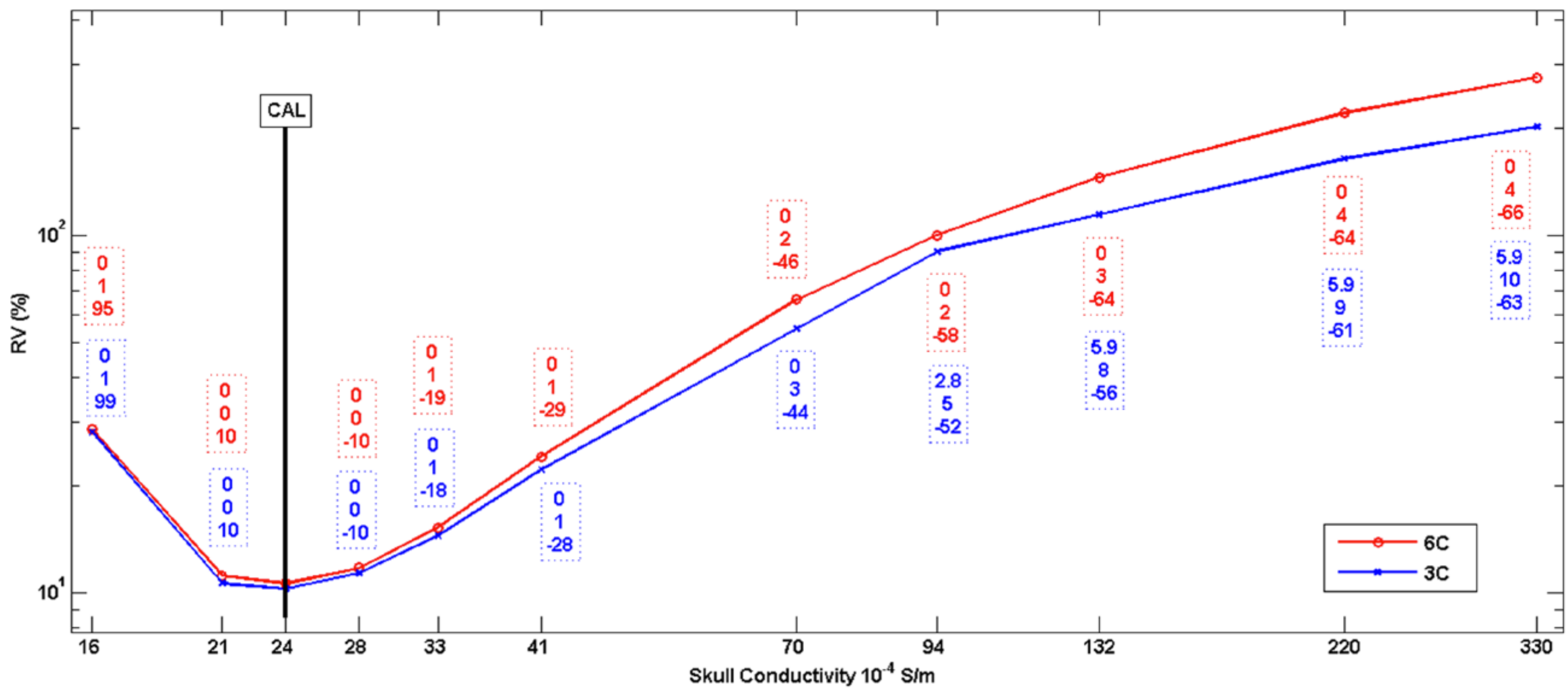

Figure 3. Skull conductivity calibration graph. RV (in %) obtained from Algorithm 2 in step 2.d. for different skull conductivity parameters for 6C (red) and 3C (blue) head models. The differences to the calibrated head models *6C_Cal* and *3C_Cal* (indicated by the black bar, see also Table 1) in source reconstruction are indicated by boxes with dashed frames: Difference in source location x (top row, in mm), orientation o_2 (middle row, in degree) and strength m_2 (bottom row, in %).

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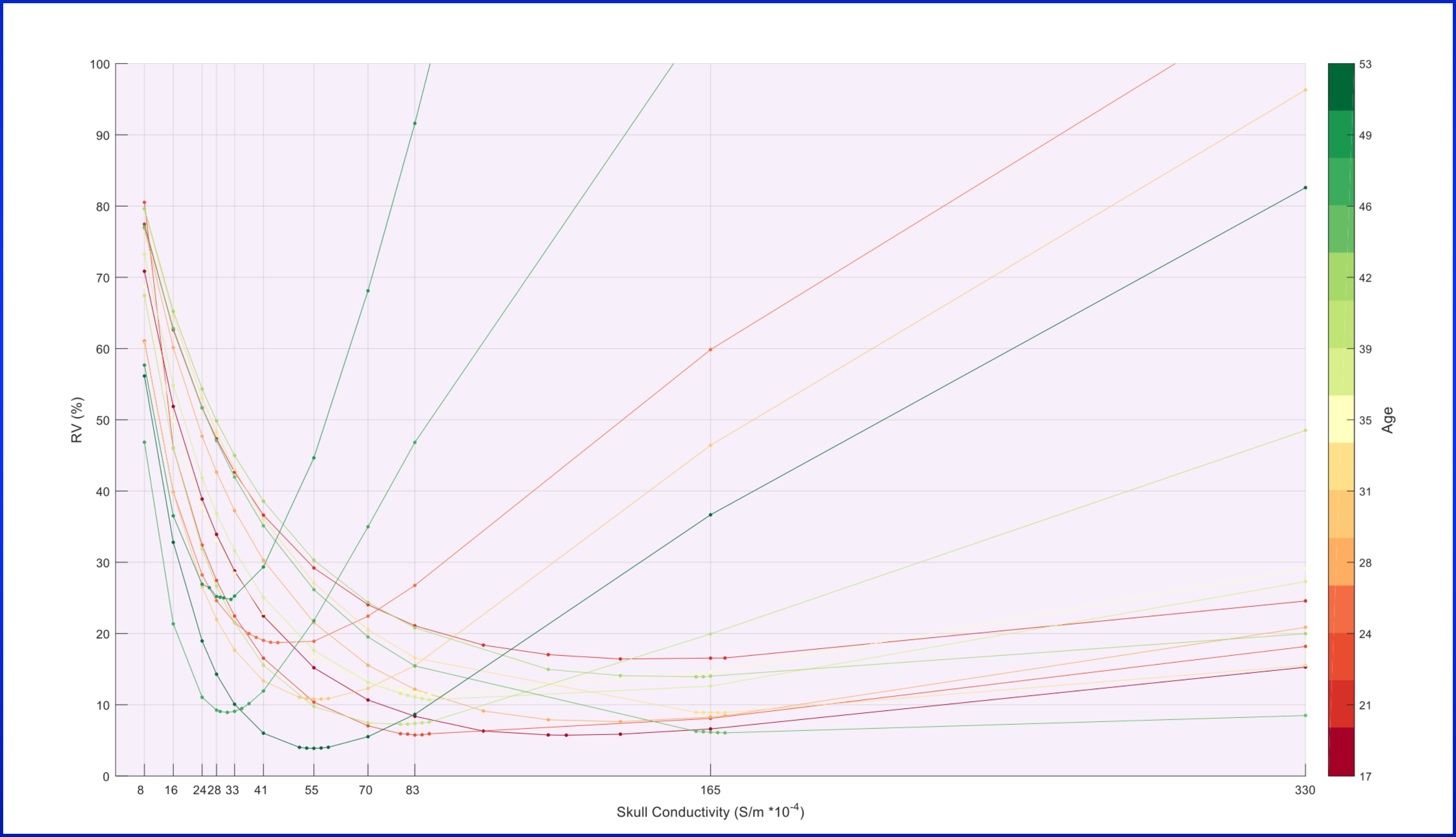
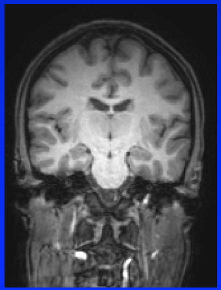
Individual skull conductivity calibration

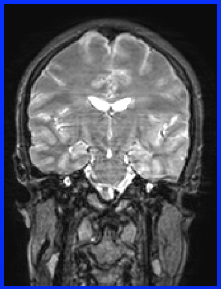


[Aydin, Vorwerk, Küpper, Heers, Kugel, Galka, Hamid, Wellmer, Kellinghaus, Rampp & Wolters, *Plos One*, 2014]

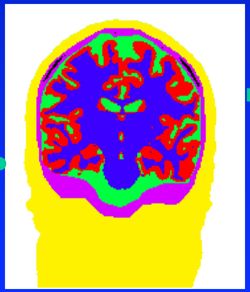
Summary: Calibrated head volume conductor modeling

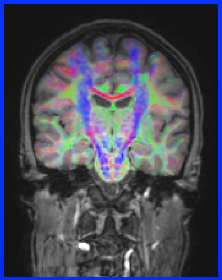
MRI measurement



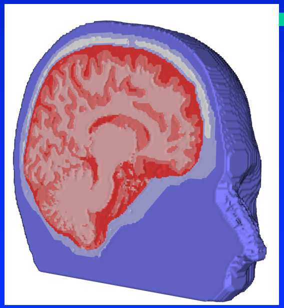


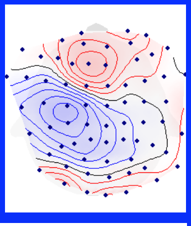
Registration Segmentation

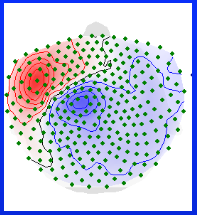




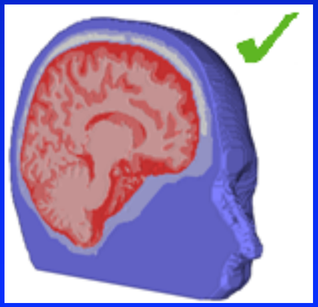
Anisotropic head model







Calibrated volume conductor model



- T1, T2, DTI (27 min)
- Medianus-nerve SEP/SEF (7 min)

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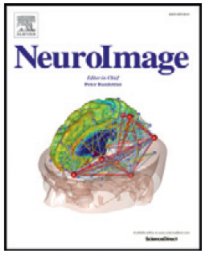

Using reciprocity for relating the simulation of transcranial current stimulation to the EEG forward problem

CrossMark

S. Wagner [a], F. Lucka [a,b,f], J. Vorwerk [a], C.S. Herrmann [c], G. Nolte [d], M. Burger [b,e], C.H. Wolters [a,e,*]

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[c] *Experimental Psychology Lab, Center for Excellence Hearing4all, European Medical School, University of Oldenburg, Oldenburg, Germany*
[d] *Department of Neurophysiology and Pathophysiology, University Medical Center Hamburg-Eppendorf, Hamburg, Germany*
[e] *Cells in Motion Cluster of Excellence, University of Münster, Münster, Germany*
[f] *Centre for Medical Image Computing, University College London, WC1E 6BT London, UK*

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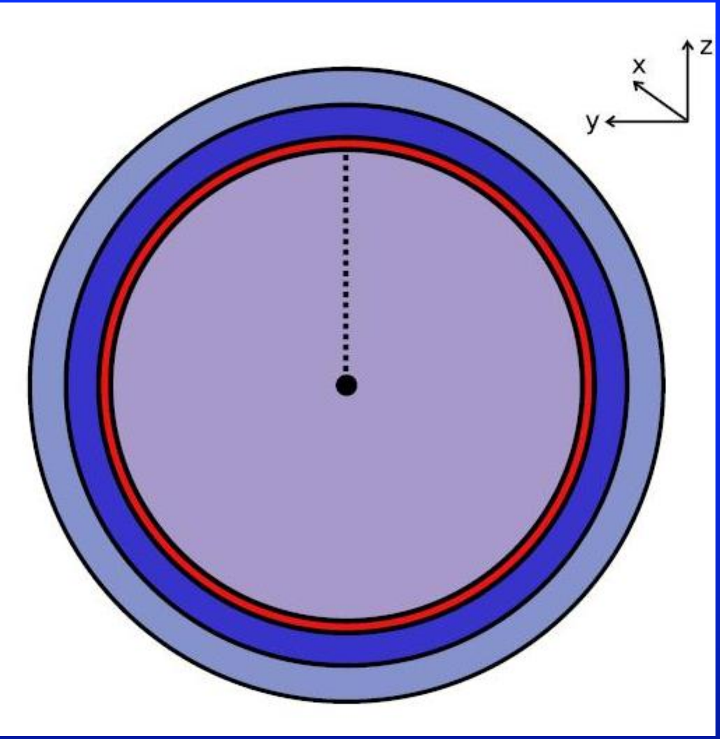
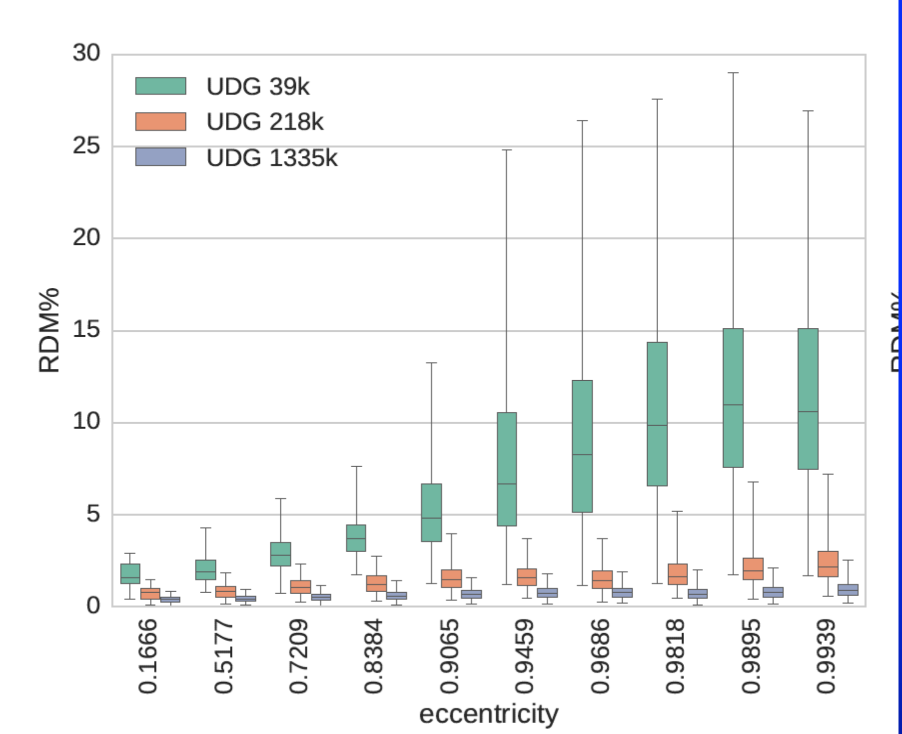
Validation of finite element method (FEM) forward modeling for the electric potential

[Nüßing, Wolters, Brinck & Engwer,…UDG-FEM for EEG..., *IEEE Trans Biomed Eng, 2016*]
[Piastra,…, Wolters, …DG-FEM for combined EEG/MEG..., *Frontiers in Neurosci., 2018*]
[Engwer, Vorwerk, Ludewig & Wolters, …DG-FEM for EEG..., *SIAM J. Sci. Comp., 2017*]
[Vorwerk, Pursiainen, Engwer & Wolters, …Mixed-FEM…, *IEEE Trans Med Imag , 2017*]
[Pursiainen, Lucka & Wolters, …complete electrode model..., *Phys.Med.Biol..*, 2012]
[Pursiainen, Vorwerk & Wolters,…H(div) source models..., *Phys Med Biol, 2016*]
[Wolters et al.,…subtraction source model..., *SIAM J. Sci. Comp.*, 2007]
[Wolters et al.,…geometry-adapted hexahedra..., *IEEE Trans. Biomed.Eng.*, 2007]
[Wolters et al.,…EEG and MEG transfer matrices..., *Inverse Problems*, 2004]
[Wolters et al.,…Algebraic Multigrid..., *Comp.Vis.Sci.*, 2002]

Validation of new FEM approaches for source analysis and brain stimulation





(a) RDM% error for radial dipoles

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Evaluation of FEM forward modeling accuracy in rabbit investigations

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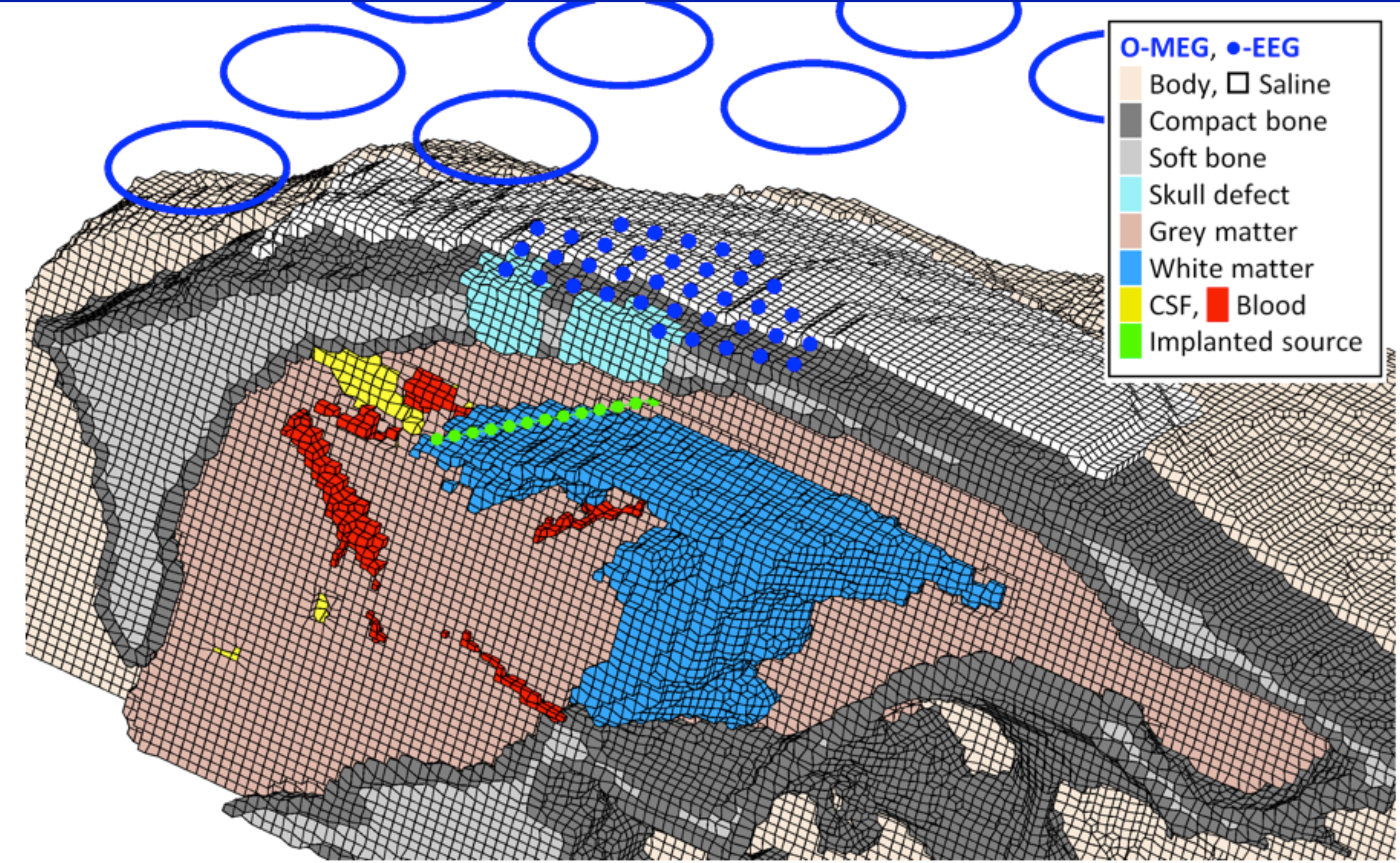
[Lau, Güllmar, Flemming, Grayden, Cook,Wolters & Haueisen, *Frontiers in Neuroscience, 2016*]

Validation in rabbit investigations



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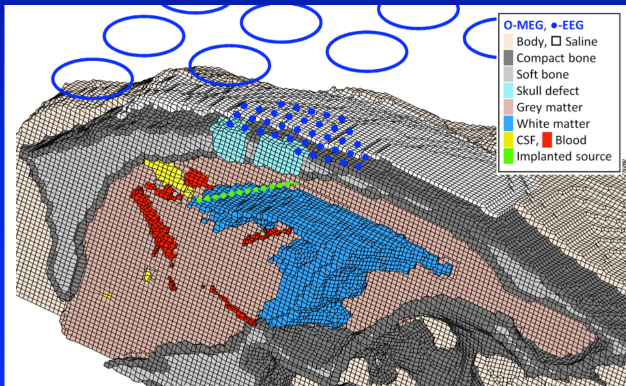
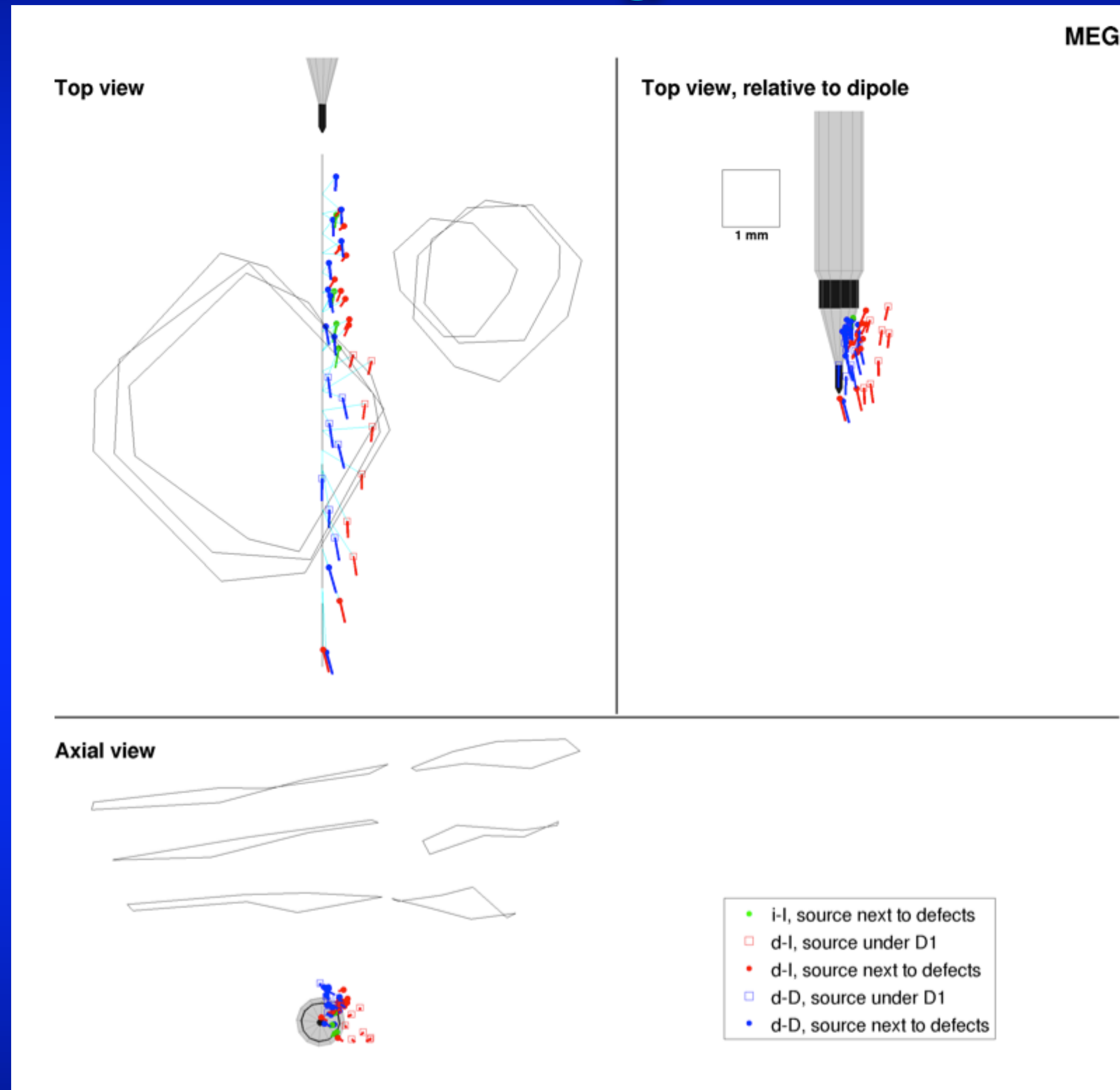
Validation in rabbit investigations





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[Vorwerk, Cho, Rampp, Hamer, Knösche & Wolters, *NeuroImage*, 2014]
[Wagner, Rampersad, Aydin, Vorwerk, Oostendorp, Neuling, Herrmann, Stegeman & Wolters, *J. Neur. Eng.*, 2014]
[Aydin, Vorwerk, Küpper, Heers, Kugel, Galka, Hamid, Wellmer, Kellinghaus, Rampp & Wolters, *Plos One*, 2014]

Guideline for volume conductor modeling

- The volume conductor model needs to contain all important tissues between the electrodes and the target brain areas
- Isotropic representations of the compartments skin, skull, CSF and brain grey and white matter are indispensable for any simulation
- The individual skull conductivity needs to be estimated (e.g. through SEP/SEF calibration)
- Skull compacta and spongiosa compartments should be distinguished, if a significant layer of spongiosa is between the electrodes and the targets
- White matter conductivity anisotropy modeling is important for deeper target areas

Software for FEM forward modeling:

- Freely available SimBio toolbox:

  https://www.mrt.uni-jena.de/simbio/index.php/Main_Page
- Freely available DUNEuro code:

  https://www.duneuro.org
- Freely available Fieldtrip-SimBio pipeline (until now only EEG):

  [Vorwerk, Oostenveld, Magyari, Wolters, *Biomed Eng Online*, 2018]

  http://www.fieldtriptoolbox.org/tutorial/headmodel_eeg_fem
- Soon: Freely available Brainstorm-SimBio/DUNEuro (NIH-funded)
- Open source SimNIBS toolbox: http://simnibs.de/
- Commercial codes: BESA MRI, CURRY8

Outline

- Literature
- Head model generation: MRI/DTI registration and segmentation and individual modeling of head tissue conductivities
- Forward problems in EEG/MEG and TES/TMS: Helmholtz reciprocity, validation work and sensitivity studies
- Target reconstruction: Combined EEG/MEG source analysis
- Inverse problem: Optimization approaches for multi-sensor tES/TMS and application to the individual stimulation of the somatosensory cortex
- Summary

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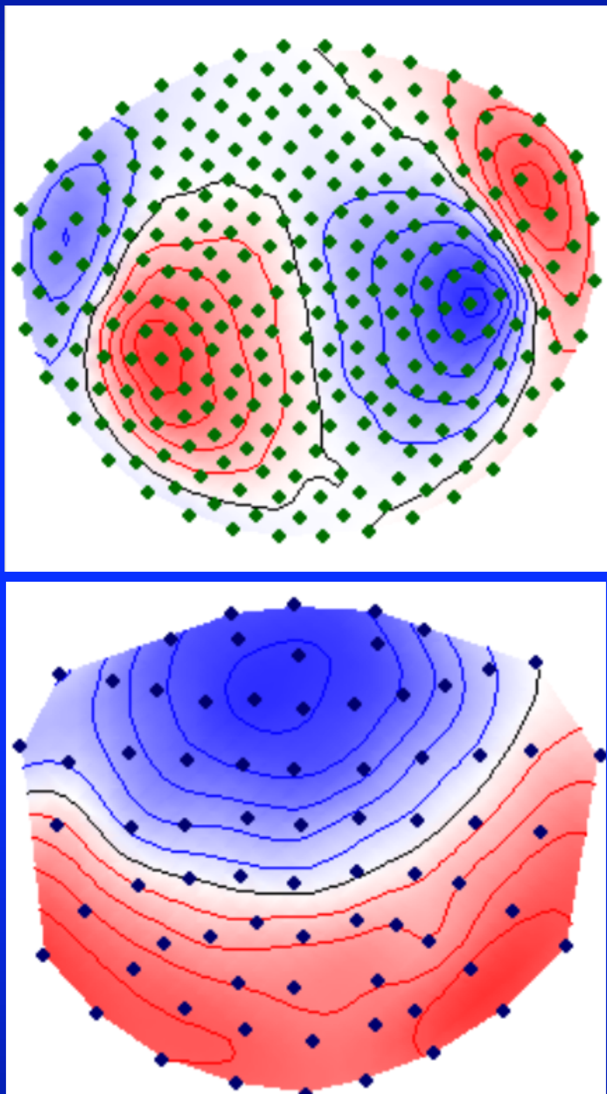
[Lew, Wolters, Anwander, Makeig & MacLeod, *Human Brain Mapping*, 2009]
[Wolters, Lew, MacLeod & Hämäläinen*, Biomed.Eng.*, 2010]
[Aydin, Vorwerk, Küpper, Heers, Kugel, Galka, Hamid, Wellmer, Kellinghaus, Rampp & Wolters, *Plos One*, 2014]

Measure combined EEG/MEG

Measure auditory evoked field (AEF) and potential (AEP) when listening to sinus-tones

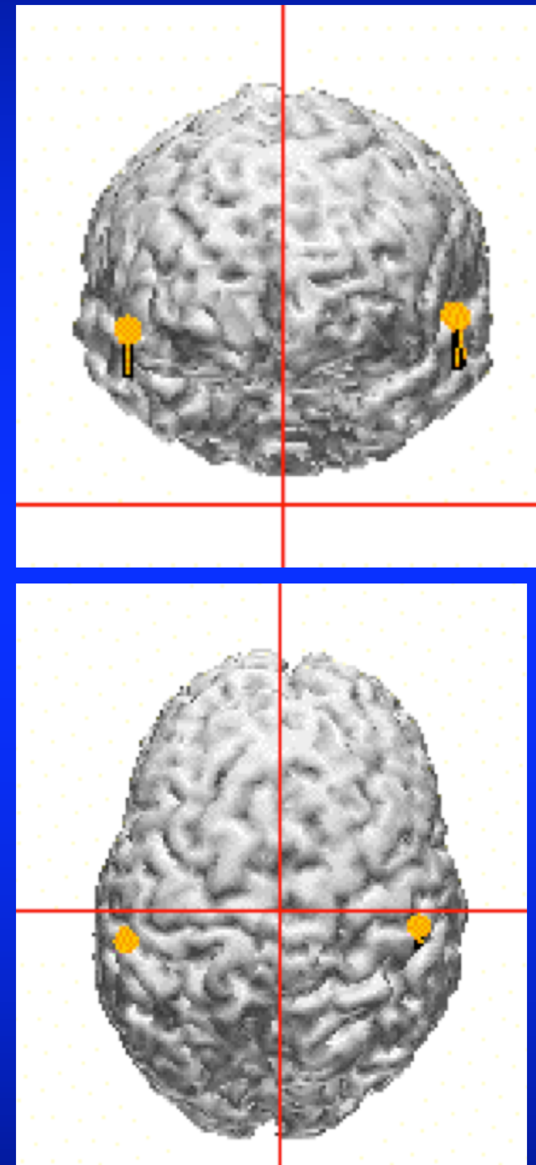
EEG/MEG source analysis

[Okamoto, Stracke, Wolters, Schmael & Pantev, *J Neurosci*, 2007]
[Lucka, Burger, Pursiainen & Wolters, *NeuroImage*, 2012]



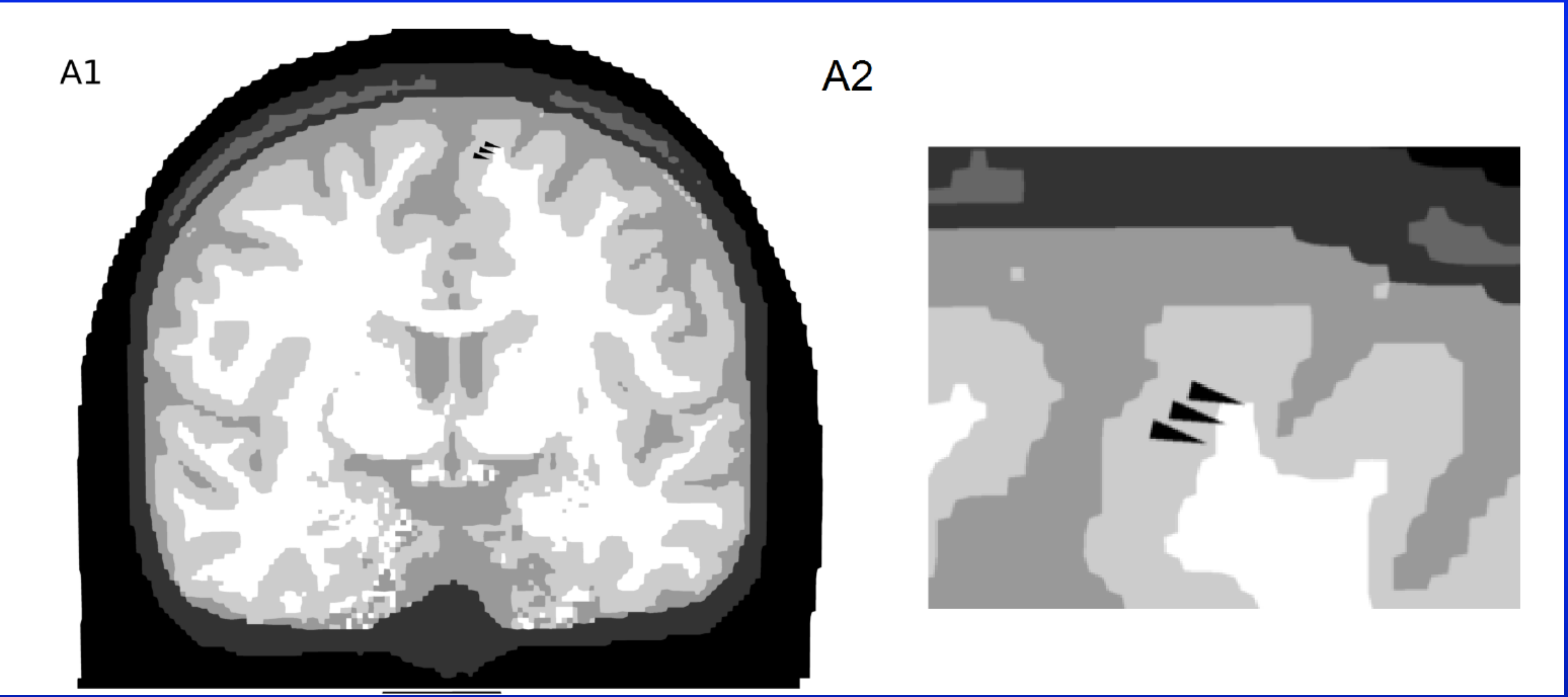
Auditory N1 component

Compute ➡ underlying sources



[Schmidt et al., *Inverse Problems*, 2002]
[Dannhauer et al., *Brain Top.*, 2013]
[Iordanov et al., *Fron Neurosci*, 2018]

Reconstructed sources might also be extended or patch-like



Software for EEG/MEG source analysis:

- Freely available SimBio toolbox:
  https://www.mrt.uni-jena.de/simbio/index.php/Main_Page
- Freely available Fieldtrip toolbox:
  http://www.fieldtriptoolbox.org
- Freely available Brainstorm toolbox:
  http://neuroimage.usc.edu/brainstorm
- Freely available MNE toolbox:
  https://martinos.org/mne/stable/index.html
- Commercial tools such as BESA or CURRY

Outline

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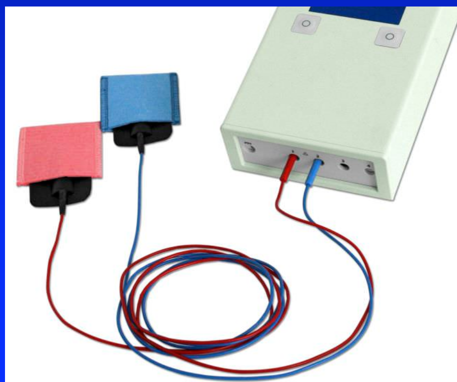
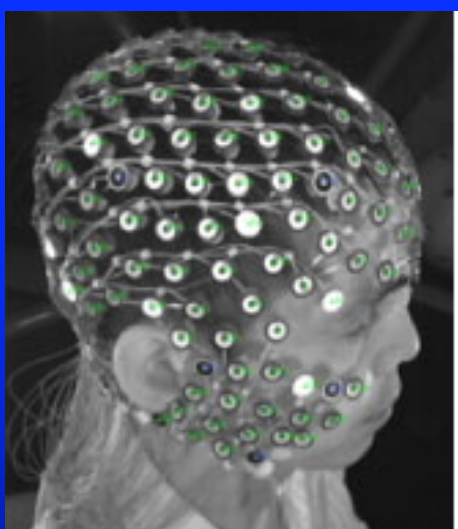
Hardware for transcranial electric stimulation (tES)



- Standard hardware for tES are two electrode patches, one anode and one cathode, used in many studies

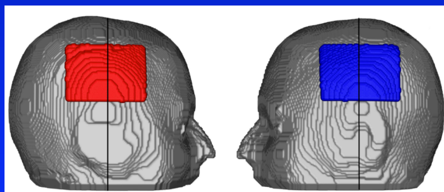


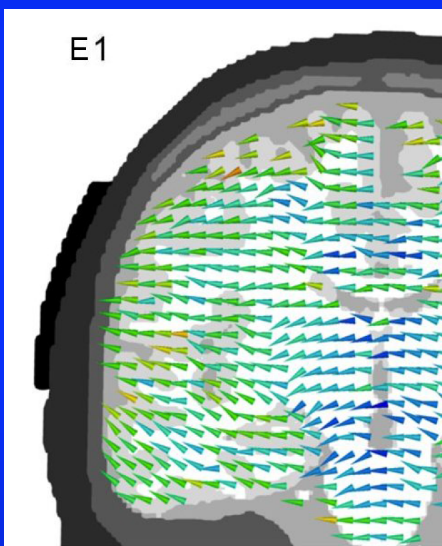
- However, first multi-electrode tES hardware and electrode optimization approaches exist, bearing the potential for much improved effects (see, e.g., Dmochowski et al., 2011,2013; Sadleir et al., 2012; Ruffini et al., 2014; Fernandez-Corazza et al., 2016; Wagner et al., 2016)

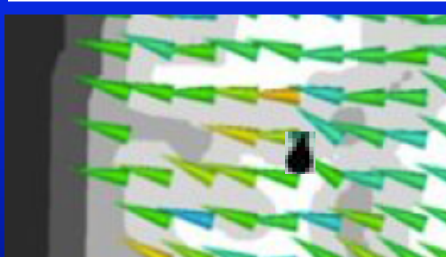
[Wagner, Burger & Wolters, *SIAM J. Appl. Math.*, 2016]
[Schmidt, Wagner, Burger, van Rienen & Wolters, *J. Neur. Eng.*, 2015]

Simulation of auditory tES

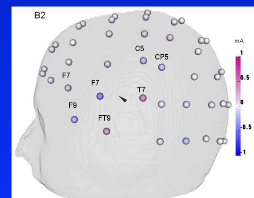
Standard two-patch

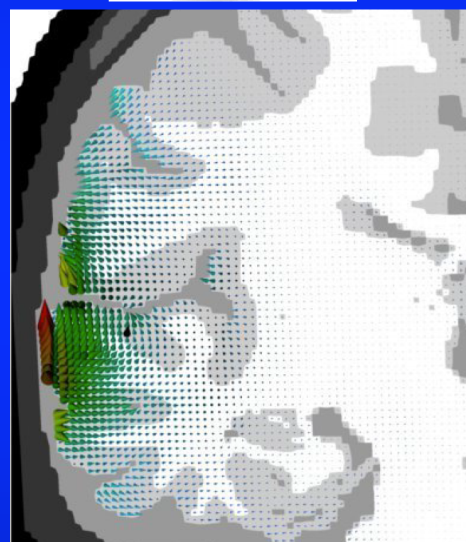


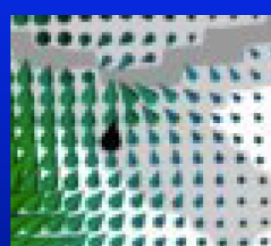




10/10 system electrodes







- Individual targeting: Electric field should be
  - maximal in area of interest
  - minimal in other areas
  - oriented radially-inwards to target cortex (Creutzfeldt et al., 1962; Krieg et al., 2013,2015; Seo, PhD thesis, 2016)

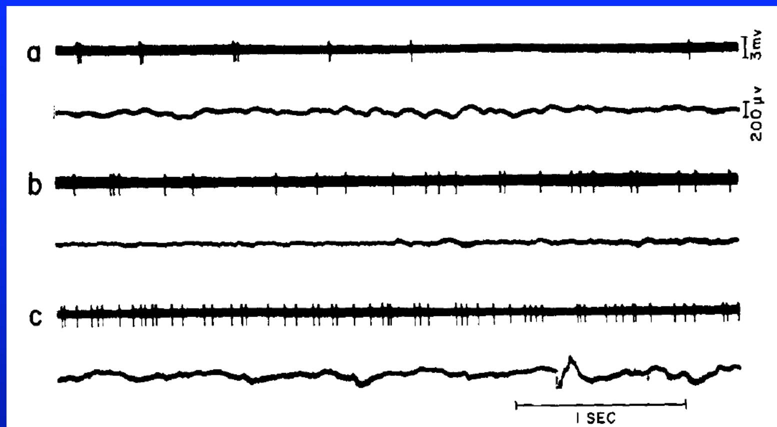


FIG. 2. Effect of transcortical d-c current on spontaneous neuron activity and EEG in the optic cortex; *a*, 500 µ outward (surface-negative); *b*, control; *c*, 500 µ inward (surface-positive).

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Mathematics for targeted multi-electrode tES

$$
\textbf{(P)} \qquad -\int_{\Omega_t} \langle \sigma \nabla \Phi, \boldsymbol{e} \rangle \, \mathrm{d}\boldsymbol{x} \to \min_{\boldsymbol{I} \in H_\diamond^{-\frac{1}{2}}(\Gamma)}
$$

$$
\begin{aligned}
\text{subject to} \qquad & \omega |\sigma \nabla \Phi| \leq \epsilon \\
& \int_{\Gamma} |\boldsymbol{I}| \, \mathrm{d}\boldsymbol{x} \leq 4 \\
& \nabla \cdot \sigma \nabla \Phi = 0 && \textit{in } \Omega \\
& \langle \sigma \nabla \Phi, \boldsymbol{n} \rangle = \boldsymbol{I} && \textit{on } \Gamma \\
& \Phi = 0 && \textit{on } \Gamma_D
\end{aligned}
$$

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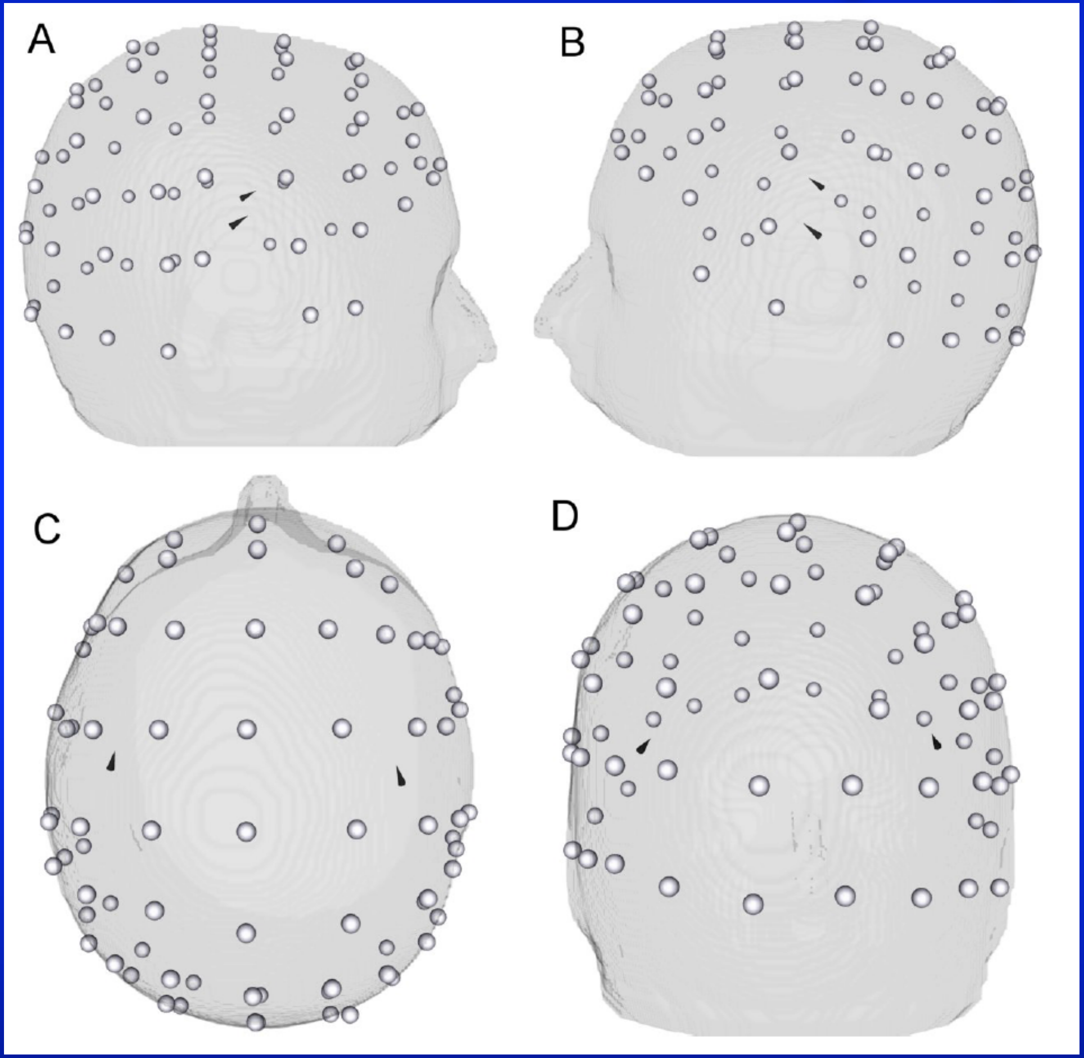
[Wagner, Burger & Wolters, *SIAM J. Appl. Math.*, 2016]
[Schmidt, Wagner, Burger, van Rienen & Wolters, *J. Neur. Eng.*, 2015]

Use individualized head model and targets (here: sources of auditory N1)…



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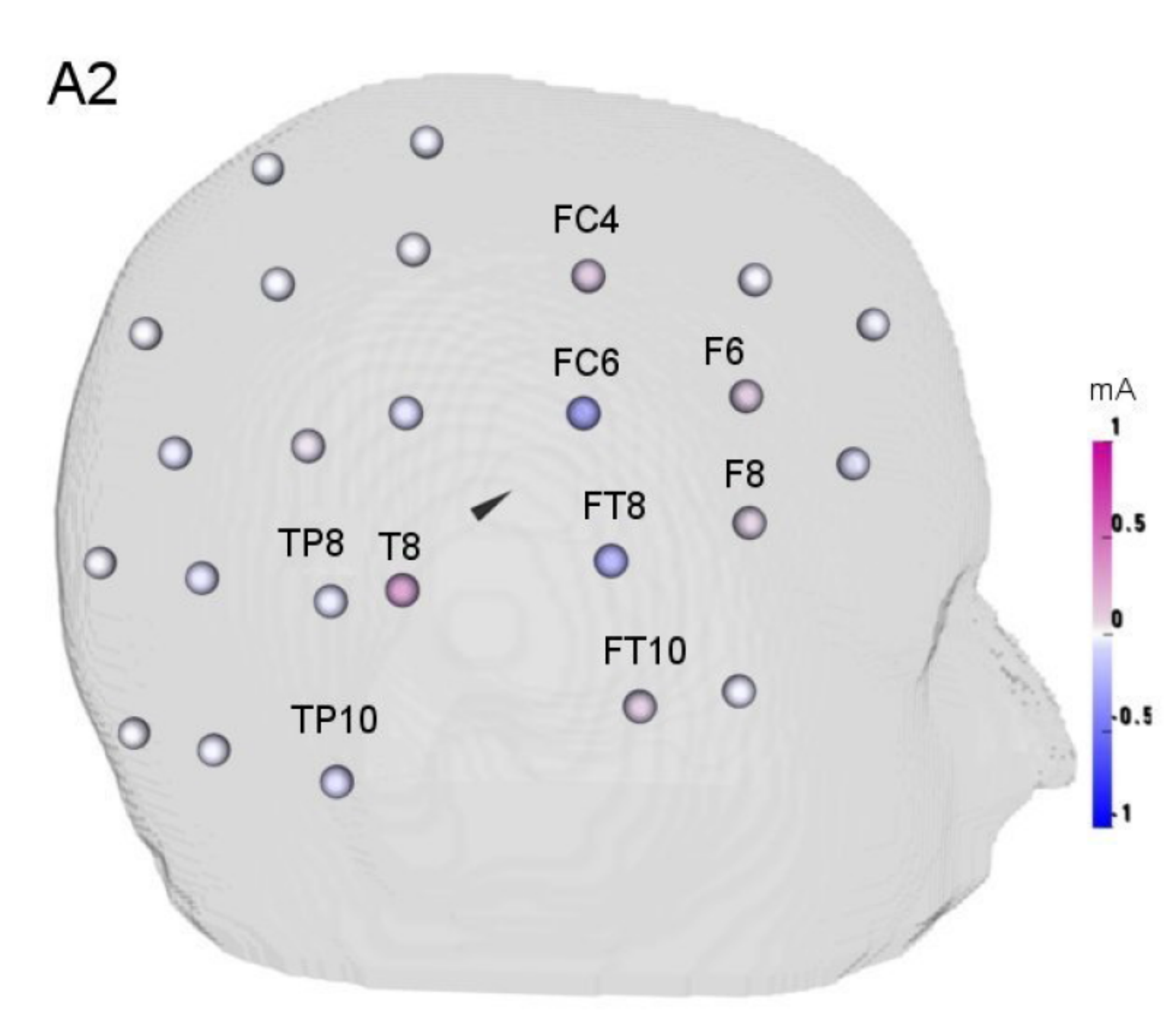
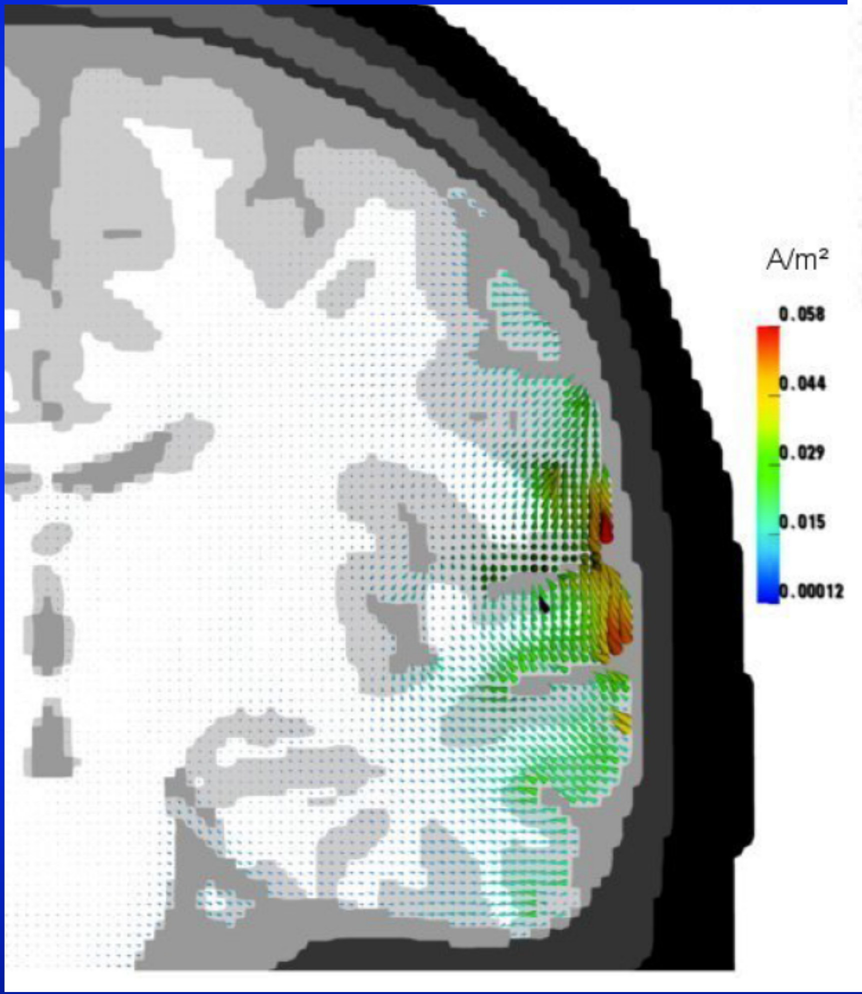
[Wagner, Burger & Wolters, *SIAM J. Appl. Math.*, 2016]
[Schmidt, Wagner, Burger, van Rienen & Wolters, *J. Neur. Eng.*, 2015]

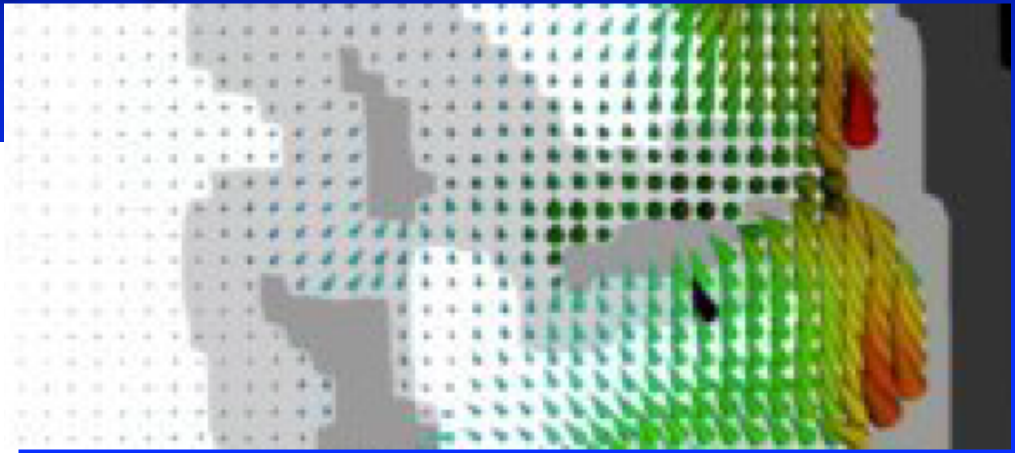
… and compute optimal multi-electrode currents…

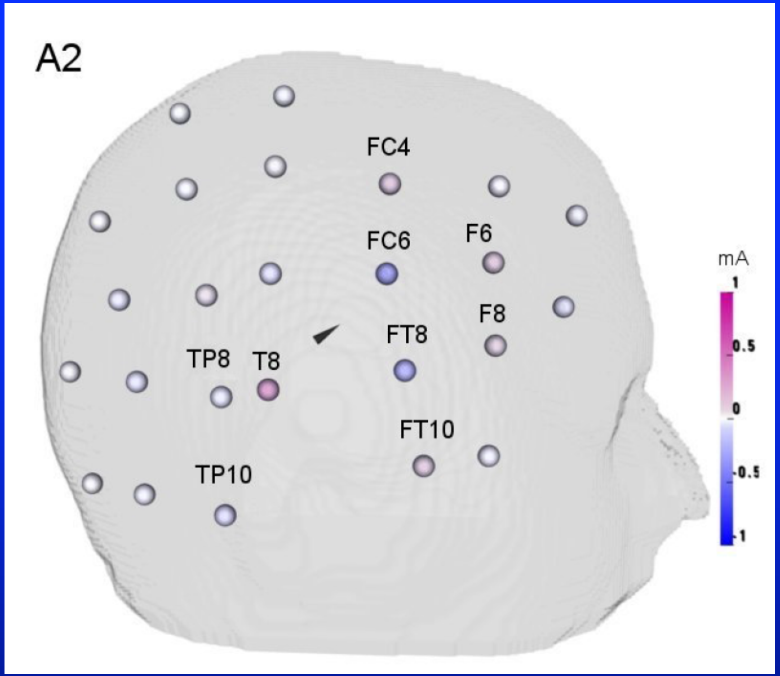


[Wagner, Burger & Wolters, *SIAM J. Appl. Math.*, 2016]
[Schmidt, Wagner, Burger, van Rienen & Wolters, *J. Neur. Eng.*, 2015]

…that lead to optimally-targeted brain currents







[Wagner, Burger & Wolters, *SIAM J. Appl. Math., 2016*]
[Wagner, PhD thesis in Mathematics, *WWU Münster,* 2015]

Mathematics for multi-coil TMS

$$
(\mathbf{P_{TMS}}) \qquad -\int_{\Omega_t} \langle \sigma \nabla \Phi, \boldsymbol{e} \rangle \, \mathrm{d}\boldsymbol{x} \rightarrow \min
$$

$$
\begin{aligned}
\text{subject to} \qquad & \omega |\sigma \nabla \Phi| \leq E_M \\
& \nabla \cdot \sigma \nabla \Phi = -\nabla \cdot \sigma \frac{\partial \boldsymbol{A}(\boldsymbol{x}, t)}{\partial t} && \mathit{in}\ \Omega \\
& \langle \sigma \nabla \Phi, \boldsymbol{n} \rangle = -\langle \sigma \frac{\partial \boldsymbol{A}(\boldsymbol{x}, t)}{\partial t}, \boldsymbol{n} \rangle && \mathit{on}\ \Gamma \\
& \Phi = 0 && \mathit{on}\ \ \Gamma_D
\end{aligned}
$$

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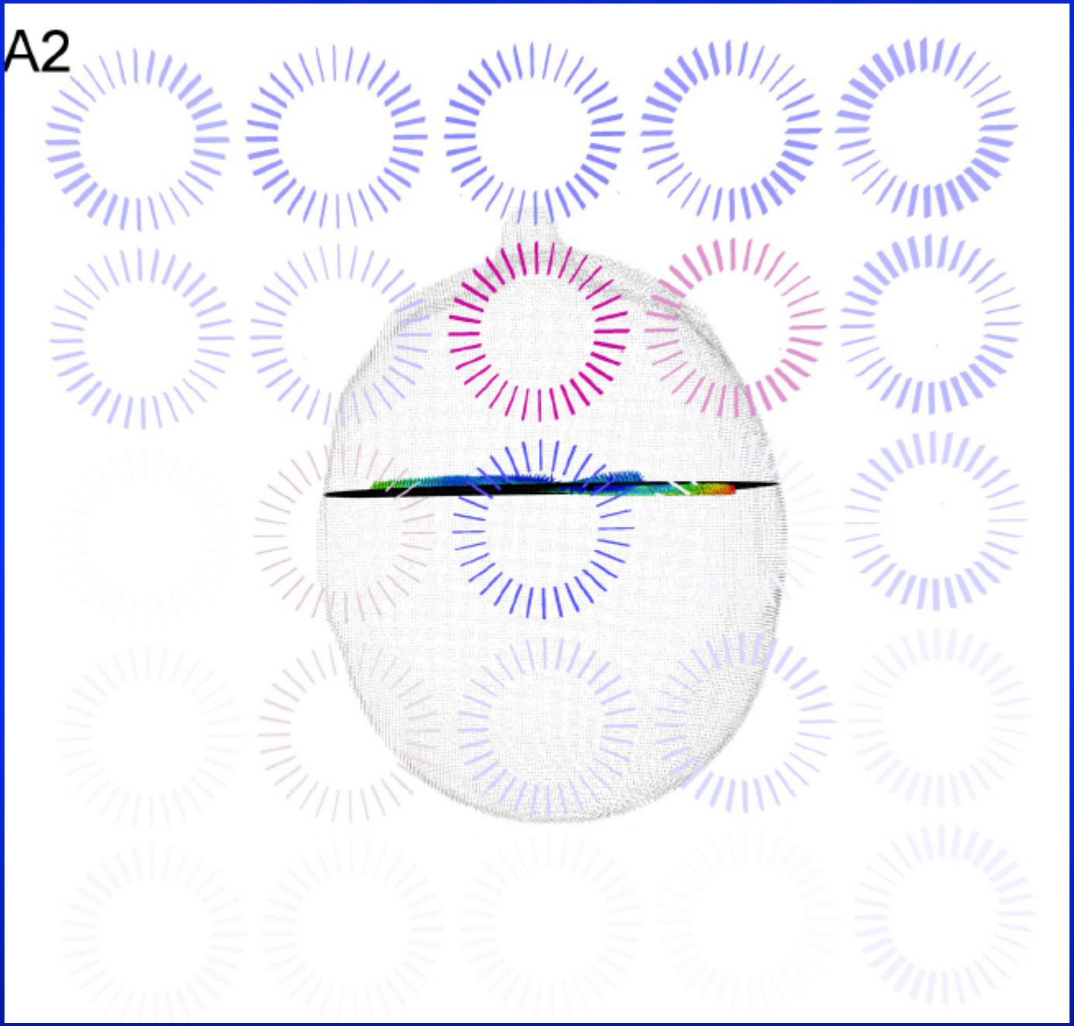
[Wagner, Burger & Wolters, *SIAM J. Appl. Math., 2016*]
[Wagner, PhD thesis in Mathematics, *WWU Münster,* 2015]

Mathematics are similar for multi-coil TMS: Use head model and targets. Software then computes optimal multi-coil TMS currents



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Evaluation of inverse optimization approaches for the stimulation of the somatosensory cortex

[Khan, Antonakakis, Vogenauer, Wollbrink, Suntrup-Krüger, Schneider, Herrmann, Nitsche, Paulus, Haueisen & Wolters, *EMBC, Berlin*, 2019]

Multi-channnel optimization for individual stimulation of somatosensory cortex

TABLE 1. Current Density (A/m^2) in target (IT), in non-target (INT) regions, directionality (DIR) and Parallity (PAR) across 4 optimization Approaches for all 4 subjects.

Subjects	*IT* (A/m^2)	*INT* (A/m^2)	*DIR* (A/m^2)	*PAR*
	2-Patch			
S1	0.0783	0.0278	0.0278	36
S2	0.1129	0.0400	0.0400	35
S3	0.1428	0.0424	0.0424	30
S4	0.0825	0.0320	0.0320	39
	MI			
S1	0.0737	0.0328	0.0572	78
S2	0.1762	0.0284	0.1341	76
S3	0.2298	0.0482	0.1783	78
S4	0.0811	0.0208	0.0653	81
	CMI			
S1	0.0716	0.0270	0.0540	75
S2	0.1613	0.0344	0.1231	76
S3	0.2141	0.0447	0.1703	80
S4	0.0844	0.0280	0.0633	75
	ADMM			
S1	0.0142	0.0019	0.0109	77
S2	0.0315	0.0027	0.0239	76
S3	0.0401	0.0014	0.0310	77
S4	0.0199	0.0014	0.0146	73

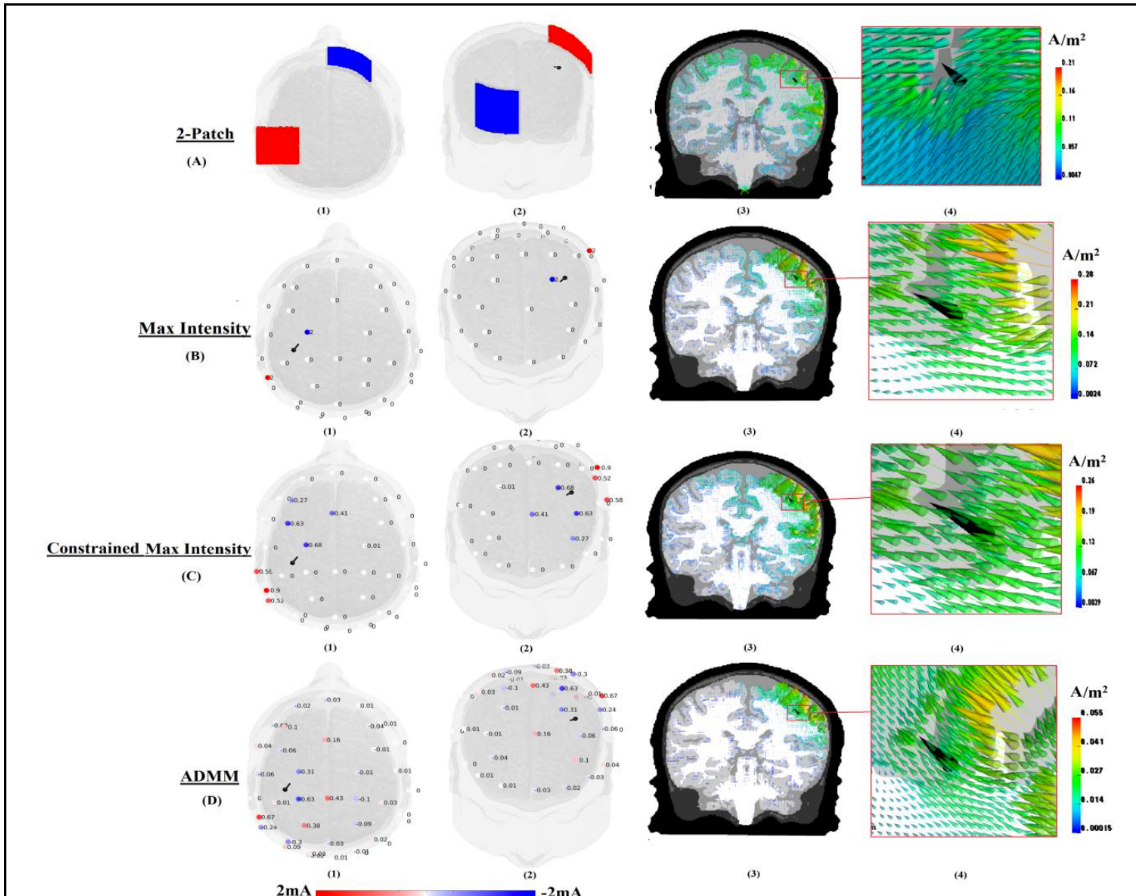

Figure 1. Current density distributions and montages with currents on stimulation electrodes for subject 2. The first and second columns A1-D1 and A2-D2 shows the simulated montages with stimulation currents in axial and frontal view respectively. The third column A3-D3 shows the current distributions for the 4 methods and the fourth column A4-D4 shows the current density vectors at the

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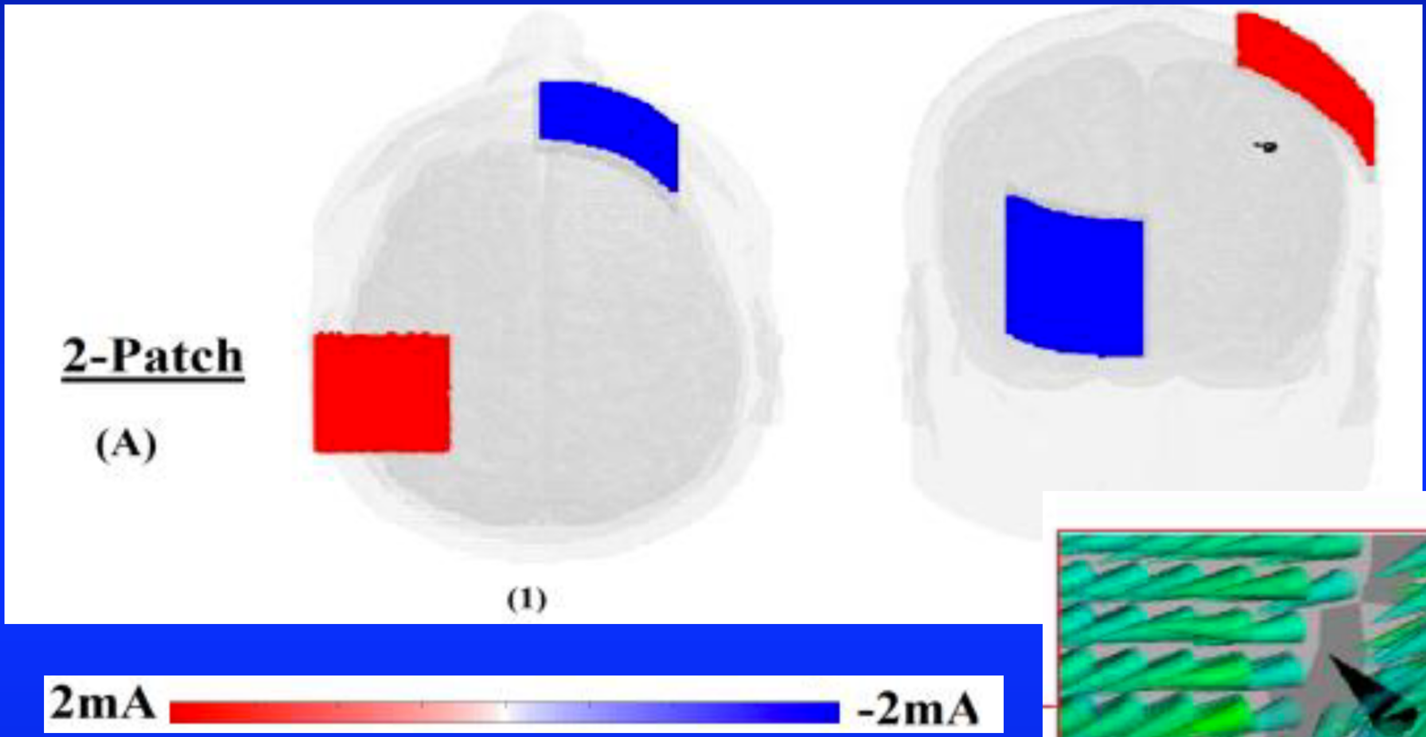
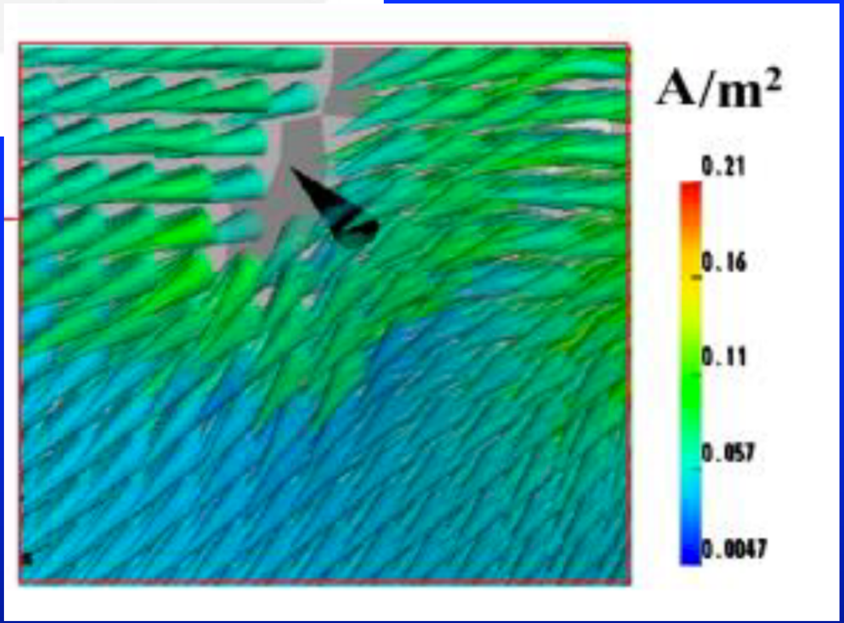
[Khan, Antonakakis, Vogenauer, Wollbrink, Suntrup-Krüger, Schneider, Herrmann, Nitsche, Paulus, Haueisen & Wolters, *EMBC, Berlin*, 2019]

2-patch TES for stimulation of somatosensory cortex



Subjects	2-Patch			
	IT (A/m²)	*INT (A/m²)*	*DIR (A/m²)*	*PAR*
S1	0.0783	0.0278	0.0278	36
S2	0.1129	0.0400	0.0400	35
S3	0.1428	0.0424	0.0424	30
S4	0.0825	0.0320	0.0320	39



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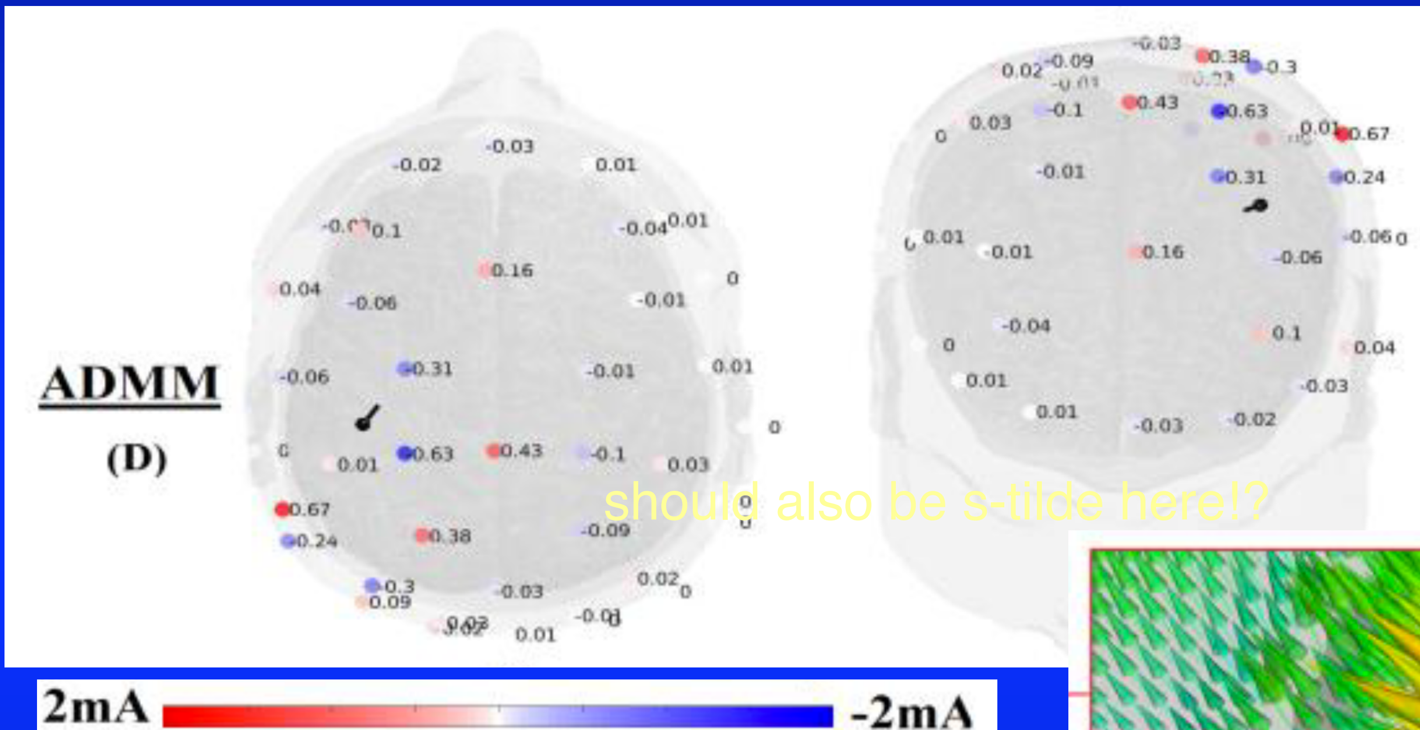
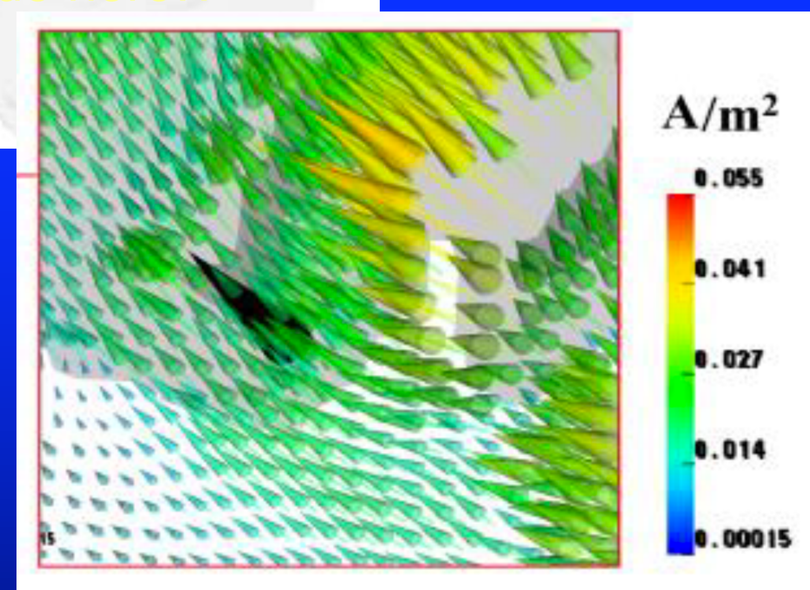
ADMM optimization for individual stimulation of somatosensory cortex



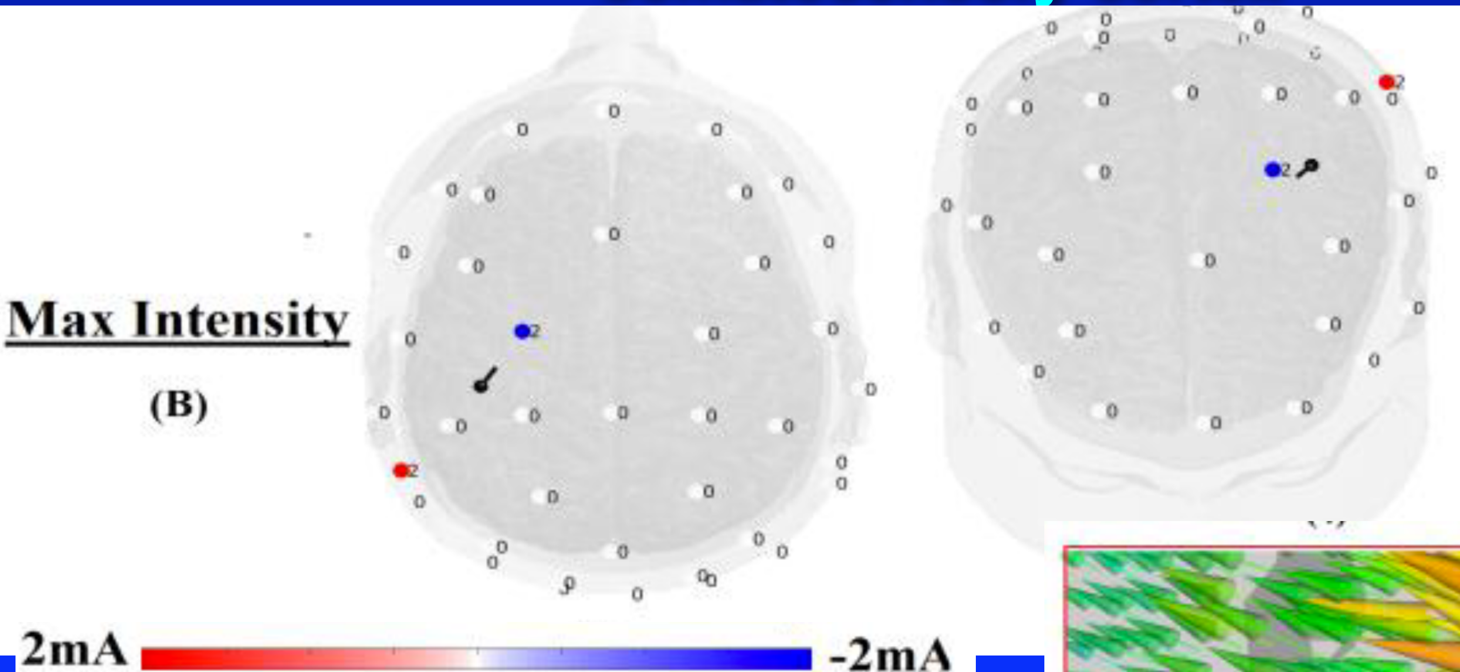
should also be s-tilde here!?

Subjects	*IT (A/m²)*	*INT (A/m²)*	*DIR (A/m²)*	*PAR*
	ADMM			
S1	0.0142	0.0019	0.0109	77
S2	0.0315	0.0027	0.0239	76
S3	0.0401	0.0014	0.0310	77
S4	0.0199	0.0014	0.0146	73

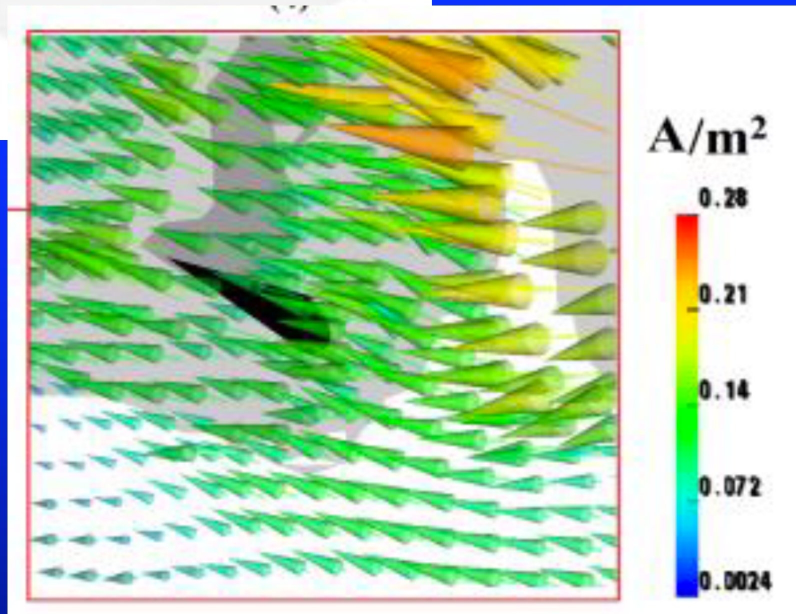


[Khan, Antonakakis, Vogenauer, Wollbrink, Suntrup-Krüger, Schneider, Herrmann, Nitsche, Paulus, Haueisen & Wolters, *EMBC, Berlin*, 2019]

Max Intensity optimization for individual stimulation of somatosensory cortex



Subjects	*IT (A/m²)*	*INT (A/m²)*	*DIR (A/m²)*	*PAR*
	MI			
S1	0.0737	0.0328	0.0572	78
S2	0.1762	0.0284	0.1341	76
S3	0.2298	0.0482	0.1783	78
S4	0.0811	0.0208	0.0653	81



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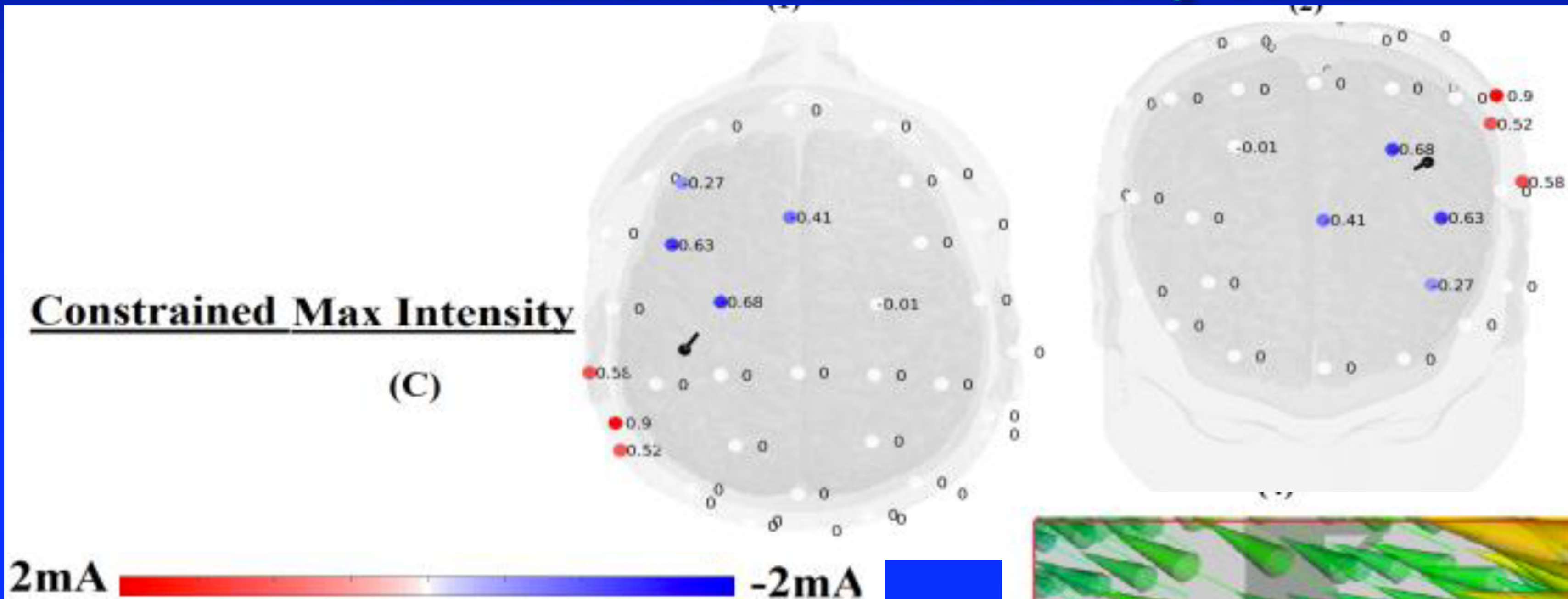
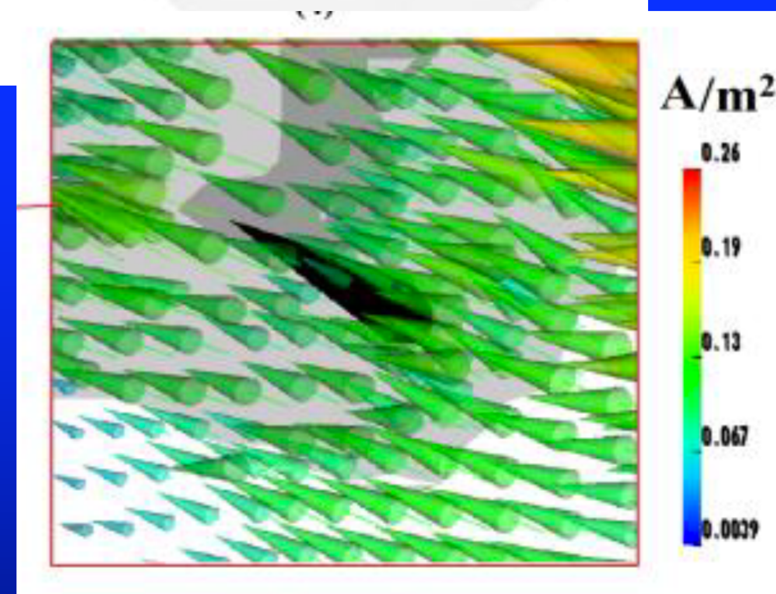
[Khan, Antonakakis, Vogenauer, Wollbrink, Suntrup-Krüger, Schneider, Herrmann, Nitsche, Paulus, Haueisen & Wolters, *EMBC, Berlin*, 2019]

Constrained Max Intensity optimization for individual stimulation of somatosensory cortex



Subjects	*IT* *(A/m²)*	*INT* *(A/m²)*	*DIR* *(A/m²)*	*PAR*
	CMI			
S1	0.0716	0.0270	0.0540	75
S2	0.1613	0.0344	0.1231	76
S3	0.2141	0.0447	0.1703	80
S4	0.0844	0.0280	0.0633	75



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Software for optimized multi-electrode TES and multi-coil TMS:

- Matlab-code for optimization (PhD theses of Sven Wagner/Asad Khan, Master theses of Simon Homölle/Nikolas Vogenauer)
- Optimizer calls freely available DUNEuro toolbox for TES forward modeling: https://www.duneuro.org
- Optimizer calls freely available SimBio toolbox for TES/TMS forward modeling: https://www.mrt.uni-jena.de/simbio/index.php/Main_Page

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Summary

- EEG/MEG contain complementary information so that combined EEG/MEG source analysis offers accurate reconstruction of both source locations and orientations -> Improved setup of targets for multi-sensor TES/TMS (Aydin et al., 2014, 2015; Antonakakis et al., 2019; Khan et al., 2019)
- Inverse multi-sensor TES/TMS problem: Optimized targeting bears potential for improvement of effects (Dmochowski et al., 2011,2013; Sadleir et al., 2012; Ruffini et al., 2014; Schmidt et al., 2015; Wagner et al., 2016; Baltus et al., 2018; Antonakakis et al., 2019; Khan et al., 2019)
- Forward multi-sensor TES/TMS problem:
  - Finite element method (FEM) based calibrated realistic (6CA) head modeling is important and optimized processing pipelines are needed (Windhoff et al., 2011; Ruthotto et al., 2012; Lanfer et al., 2013; Miranda et al., 2013; Aydin et al., 2014,2015; Opitz et al., 2015; ; Antonakakis et al., 2019; Khan et al., 2019)
  - With unfitted FEM we avoid numerical artifacts and achieve best numerical accuracy in realistic head models without topological restrictions, while avoiding complicated FEM meshing strategies (Nüßing, PhD thesis, 2018; Nüßing et al., IEEE TBME, 2016; Engwer et al., SIAM Sci. Comp., 2017)

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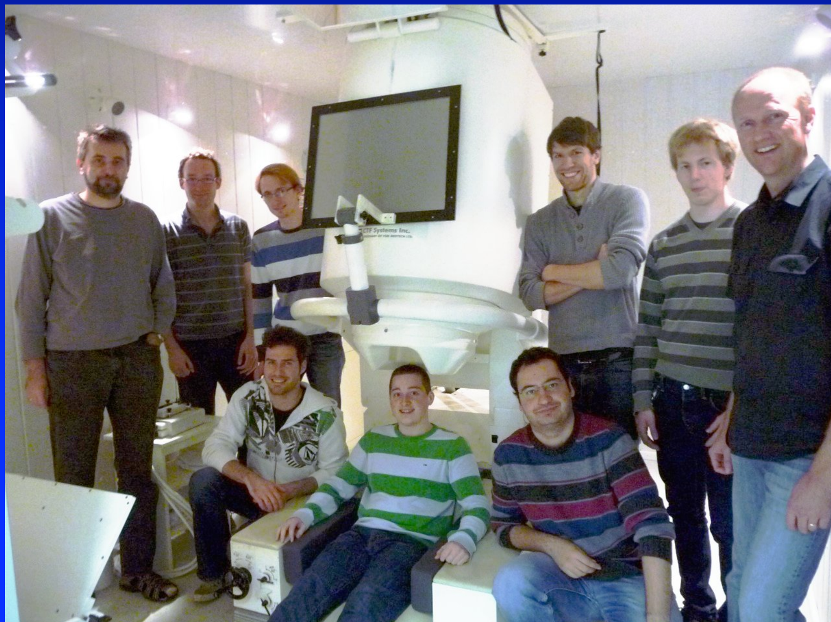
Thank you for your attention!



2010-2016

Since 2016

Münster SIM-NEURO workgroup

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