Next Generation EEG Nets that cloak at MRI and CT

IEEE P2010 Working Group (Individual-based)

EEG-fMRI was first developed as a clinical tool for epilepsy presurgical mapping. However, given its complexity after almost 30 years, EEG-fMRI is still not part of any routine clinical work up. Even any type of EEG are usually removed before MRI/CT because of the presence image artifacts.

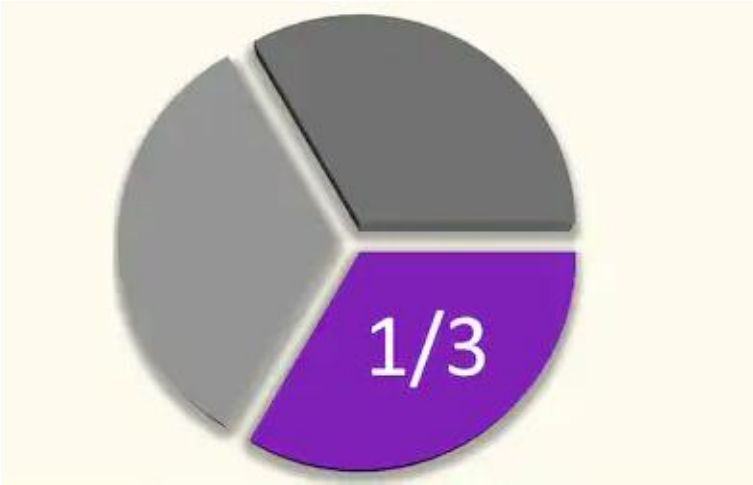
Giorgio Bonmassar

Massachusetts Hospital, Harvard Medical School

Boston, MA (USA)

November 11th, 2020

Problem



- 3.5 million American have active epilepsy
- 1/3 are medically refractory
- Many patients with challenging seizure management left out of surgery

50% surgical candidates

Epilepsy Care

Seizure

Epilepsy diagnosis

Medication trials

Imaging for pathology

Medical intractability

Surgical Consideration

Surgical workup

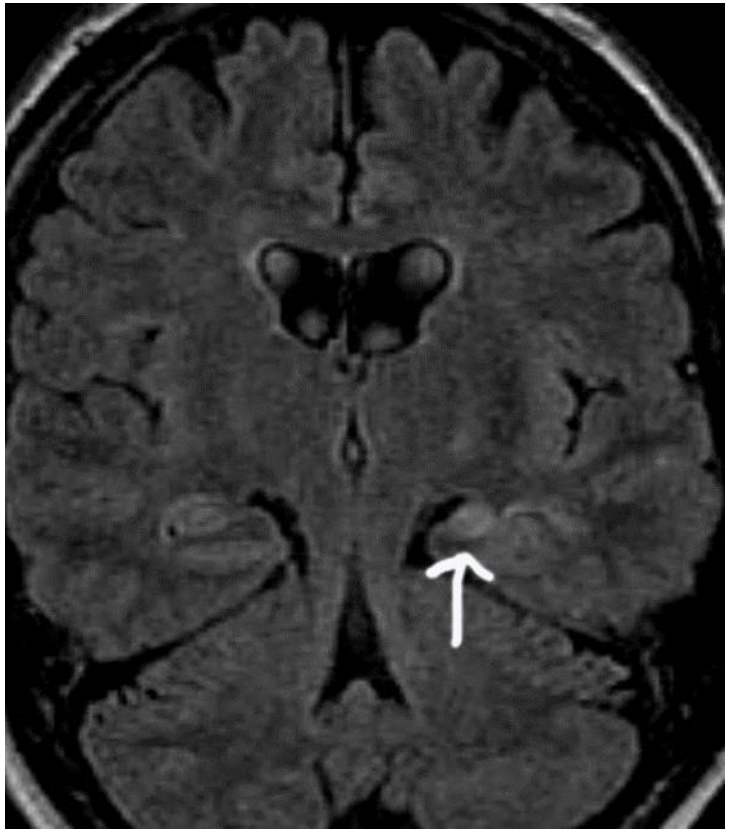
Surgery

Candidates for Epilepsy Surgery

- Persistent seizures despite appropriate pharmacological treatment
  - Usually at least two drugs, appropriate to seizure type, at adequate doses, with adequate compliance
- Impairment of quality of life due to ongoing seizures
  - Loss of driving privileges, employment opportunities, social/cultural stigma, dependence on others, side effects of medications, under achievement in school, memory deficit, attention deficit, injuries, accidents

Presurgical Evaluation- MRI

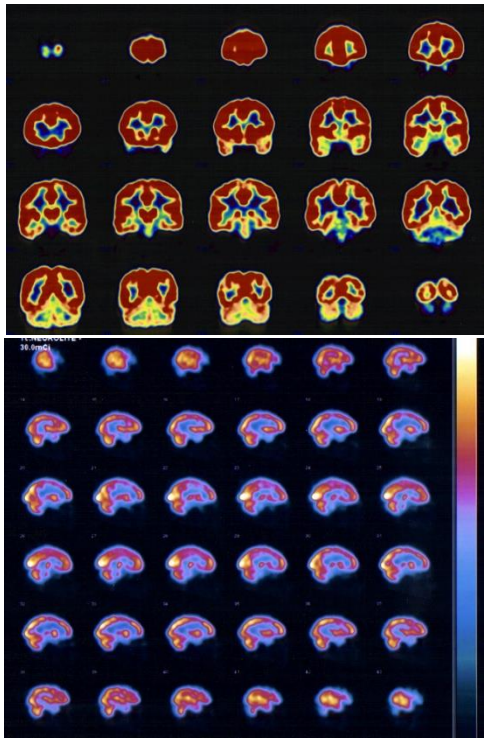
Left mesial temporal sclerosis



American Epilepsy Society

Presurgical Evaluation- PET/SPECT

- Functional Imaging
  - PET
    - hypometabolism interictally
  - SPECT
    - hypoperfusion interictally
    - hyperperfusion ictally
  - PET and/or SPECT may be coregistered with MRI



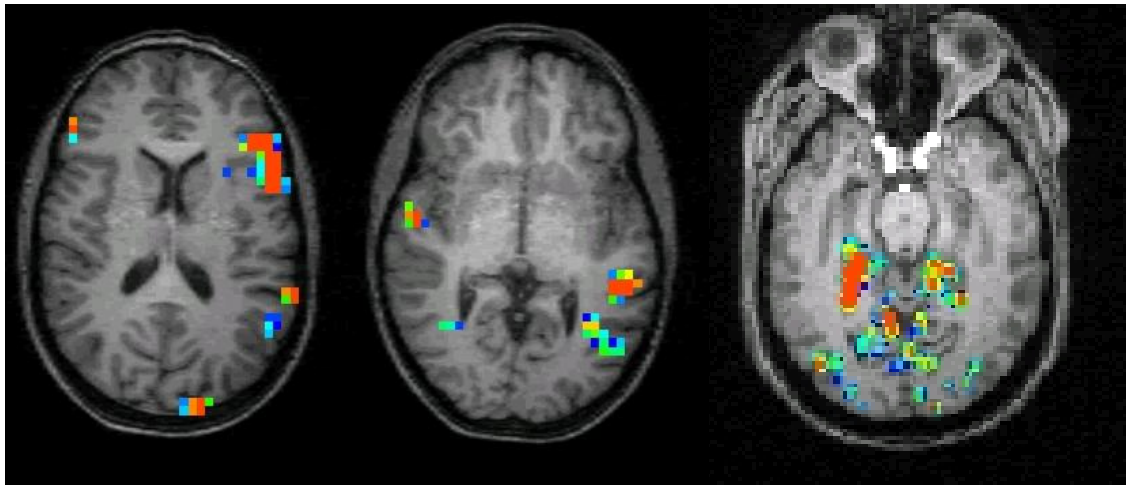
Presurgical evaluation - fMRI

fMRI- language lateralization, hippocampus function, epileptogenic focus assessment

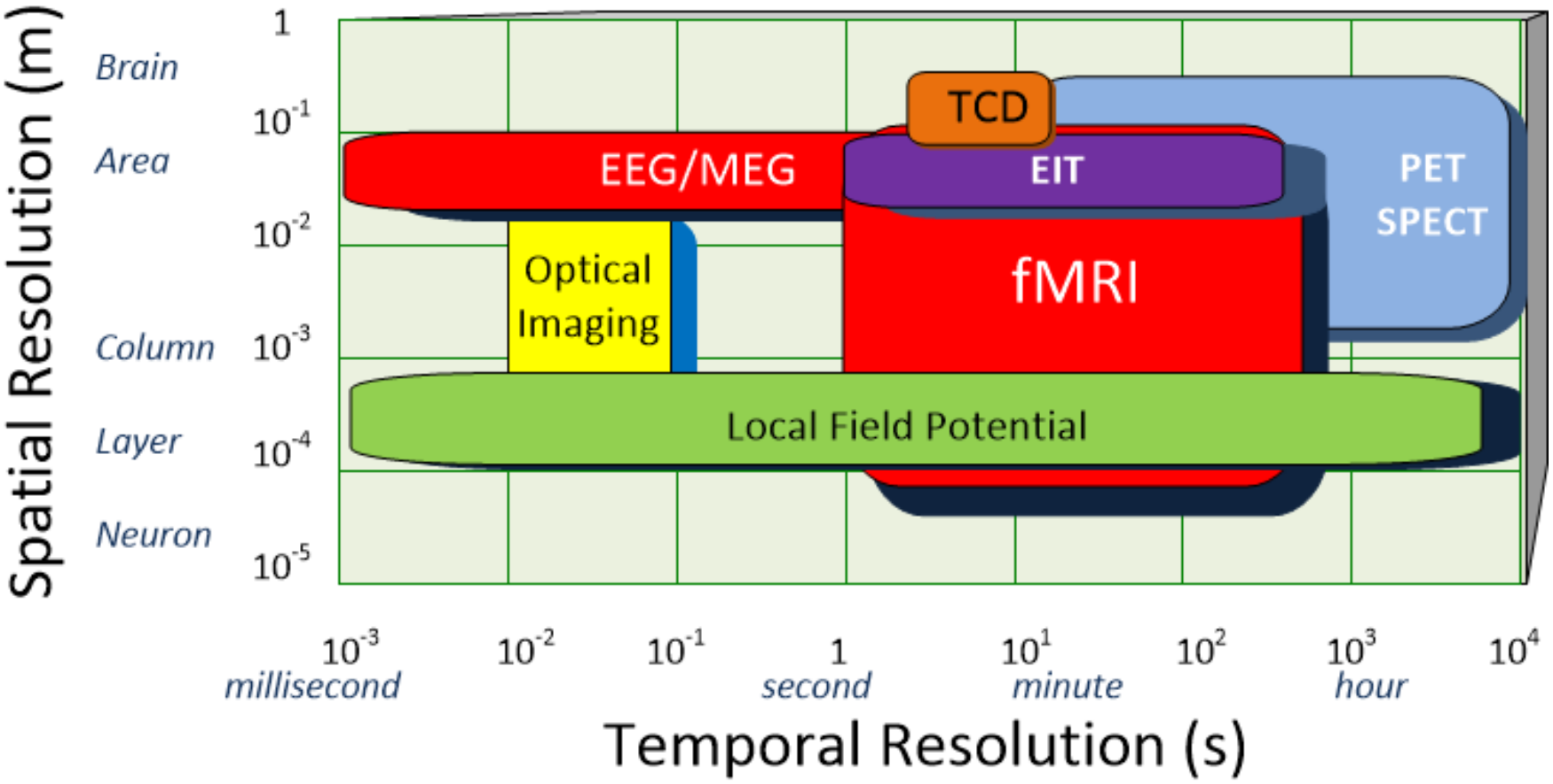
Patient with left temporal lobe epilepsy.

Left: Language mapping with verb generation task - activation in Broca's and Wernicke's areas.

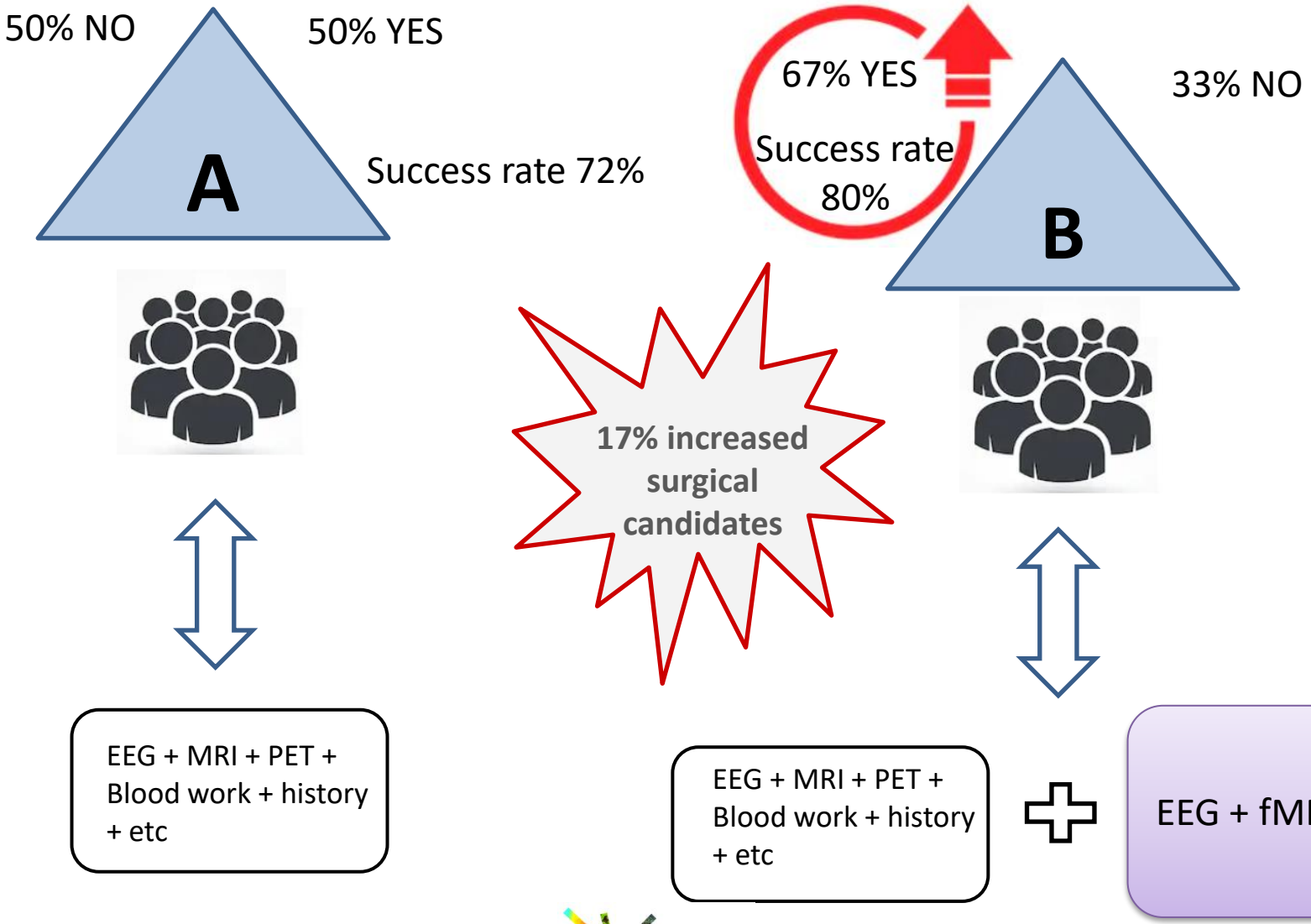
Right: Memory localization with picture encoding task - decreased activation in the left hippocampus.



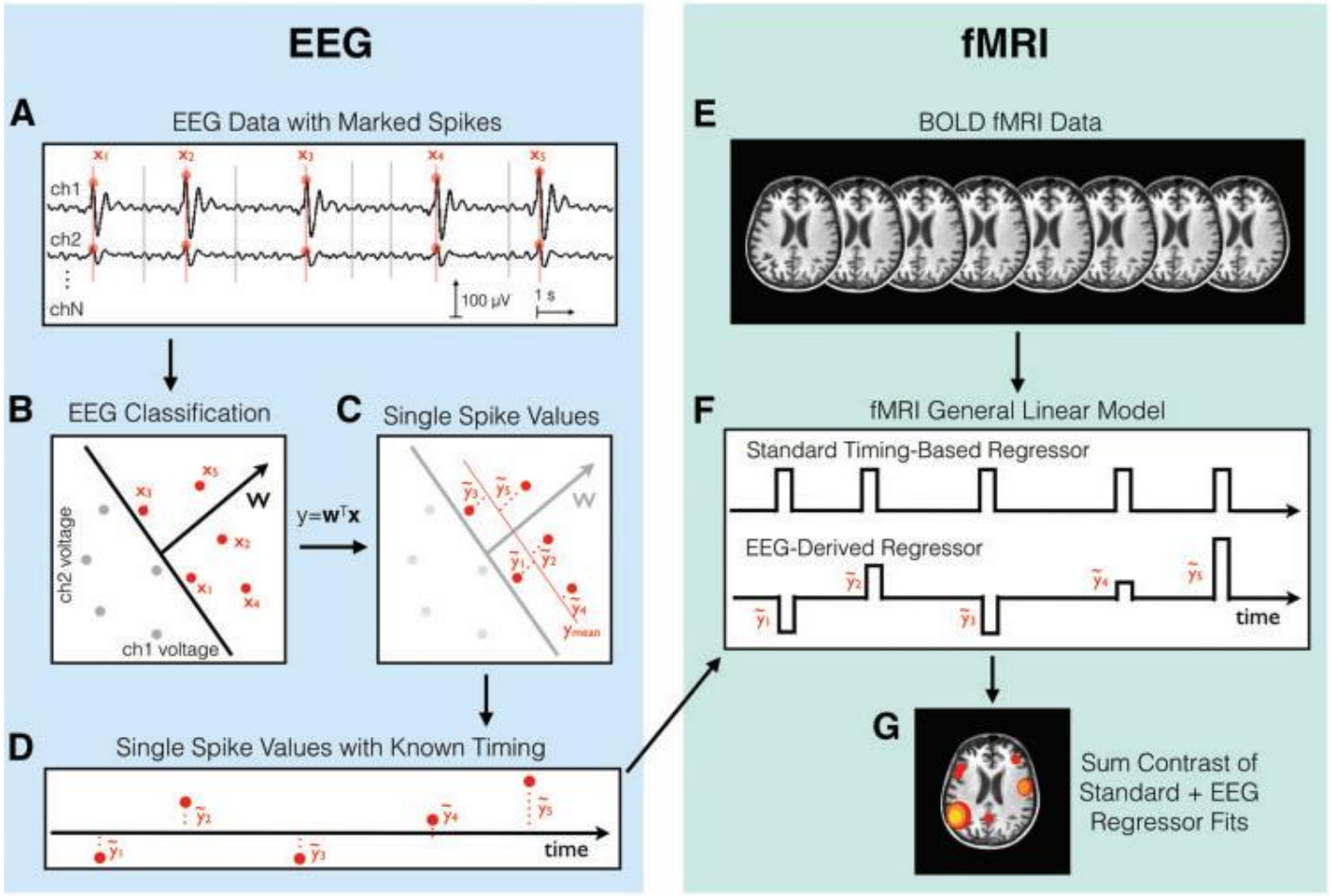
Resolution


Spatial Resolution (m)
1
Brain
10^{-1}
Area
10^{-2}
10^{-3}
Column
10^{-4}
Layer
10^{-5}
Neuron
TCD
EEG/MEG
EIT
PET
SPECT
Optical Imaging
fMRI
Local Field Potential
10^{-3}
millisecond
10^{-2}
10^{-1}
1
second
10^{1}
minute
10^{2}
10^{3}
hour
10^{4}
Temporal Resolution (s)

Supporting evidence

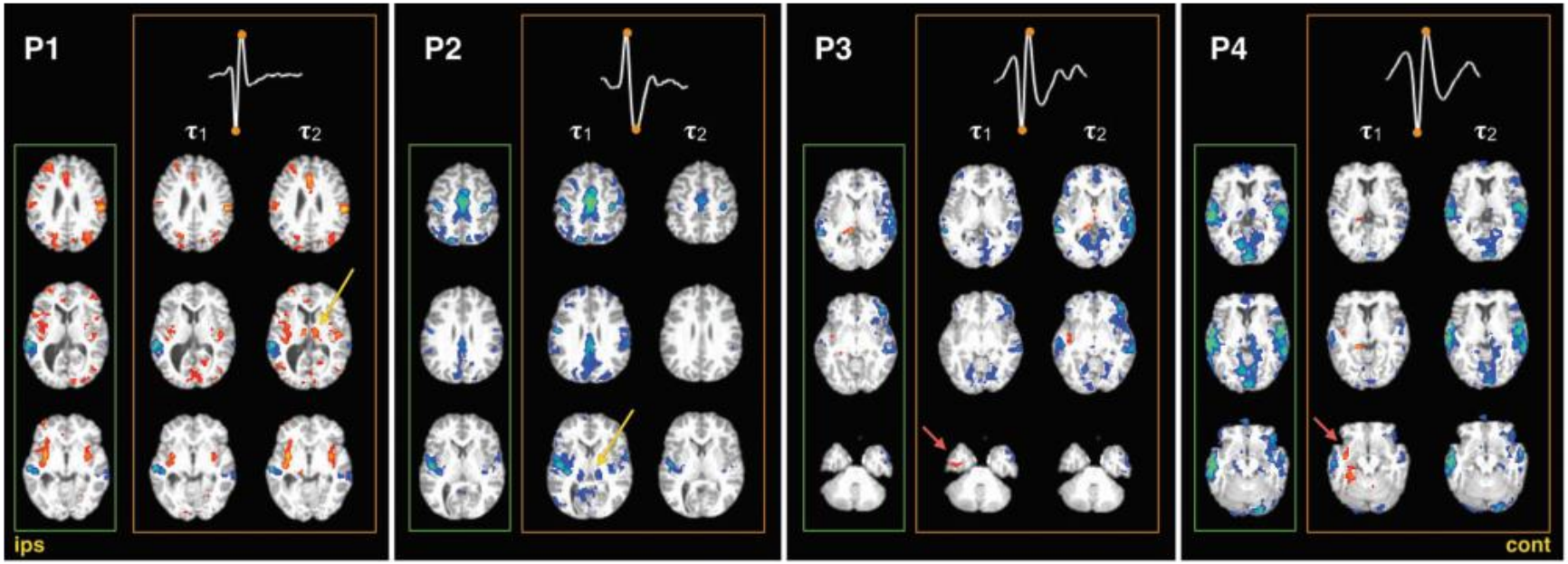


Functional MRI model derived from spike variability within a specific temporal EEG window



Walz, et al. Brain, 2017

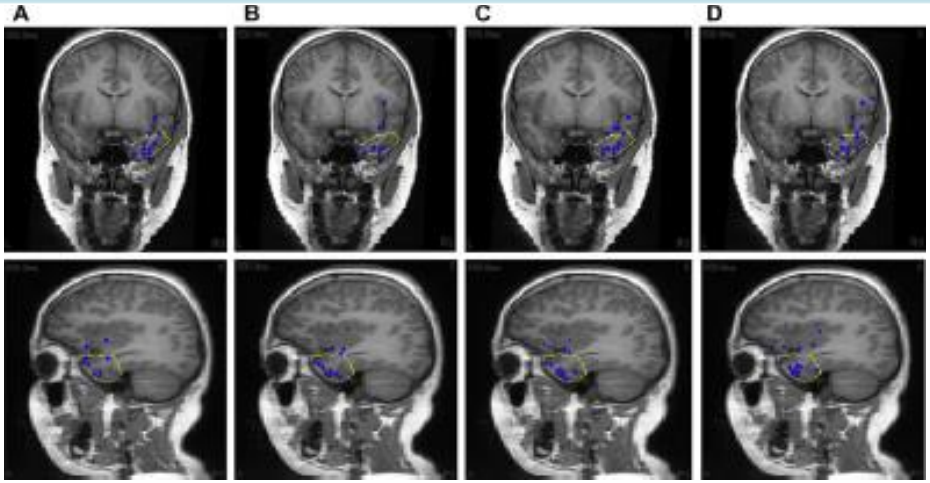
Functional MRI model derived from spike variability within a specific temporal EEG window



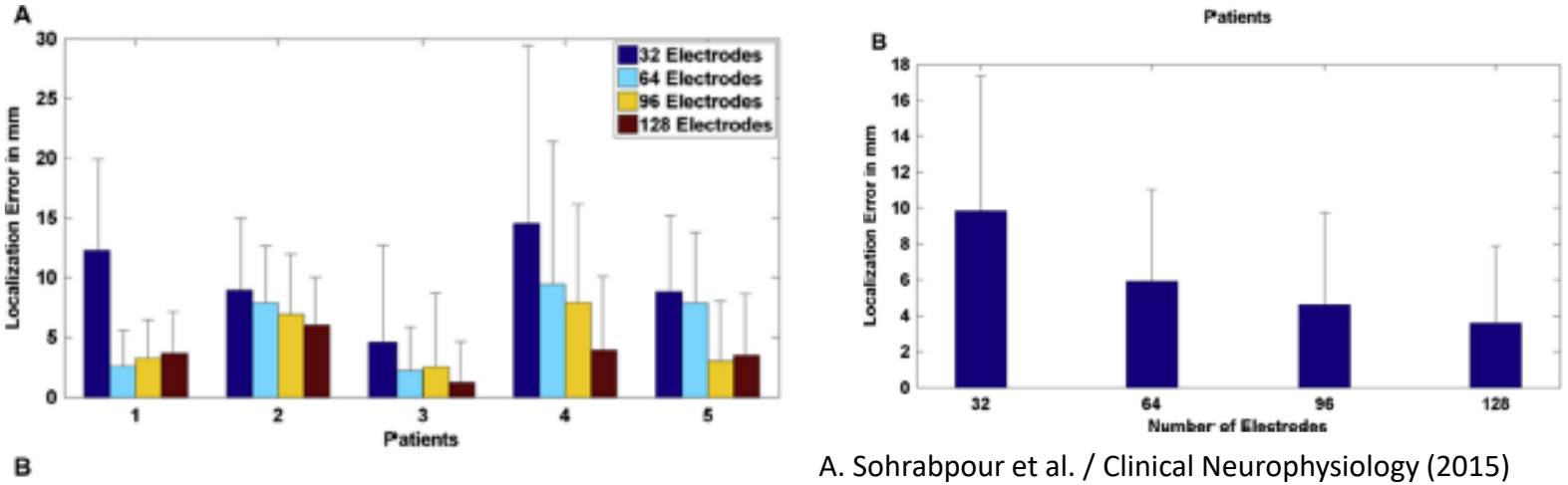
Results of standard analysis (green box) and spike amplitude coupling analyses (orange box) for four patients whose spikes displayed distinct positive and negative components. The mean spike at the electrode with highest spike magnitude and two temporal analyses ($\tau 1$ and $\tau 2$, columns) are marked with orange points. In Patients 1 and 2 (P1 and P2), all activated networks of the standard result couple strongly with a single time period and additionally reveal bilateral thalamic coupling (yellow arrows) not seen in the standard result. In Patients 3 (P3) and 4 (P4), the spike coupling analysis reveals ipsilateral regions undetectable using the standard method (red arrows).

Walz, et al. Brain, 2017

Presurgical Evaluation- EEG



The source location of all interictal spikes using: (A) 128, (B) 96, (C) 64 and (D) 32 electrodes.



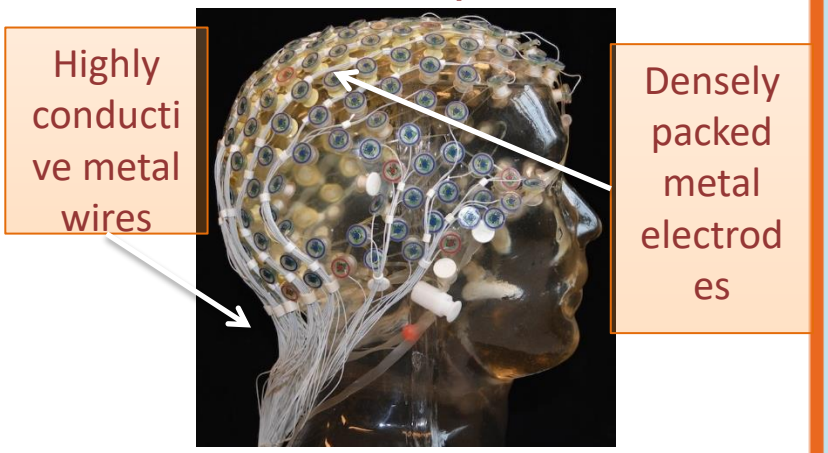
A. Sohrabpour et al. / Clinical Neurophysiology (2015)

The High-Density EEG Nets

High density EEG is widely used in Neuroscience because the advantages offered by high-resolution EEG.

What are the costs of HD-EEG in terms of safety and MRI quality especially at high-fields?

HCGSN EEG cap



1. EEG equipment can introduce susceptibility-based artifacts and cause RF inhomogeneity

2. Excess heating due to RF energy dissipation in the electrodes from induced currents, picked up by the wires as antennas (the “antenna effect”).

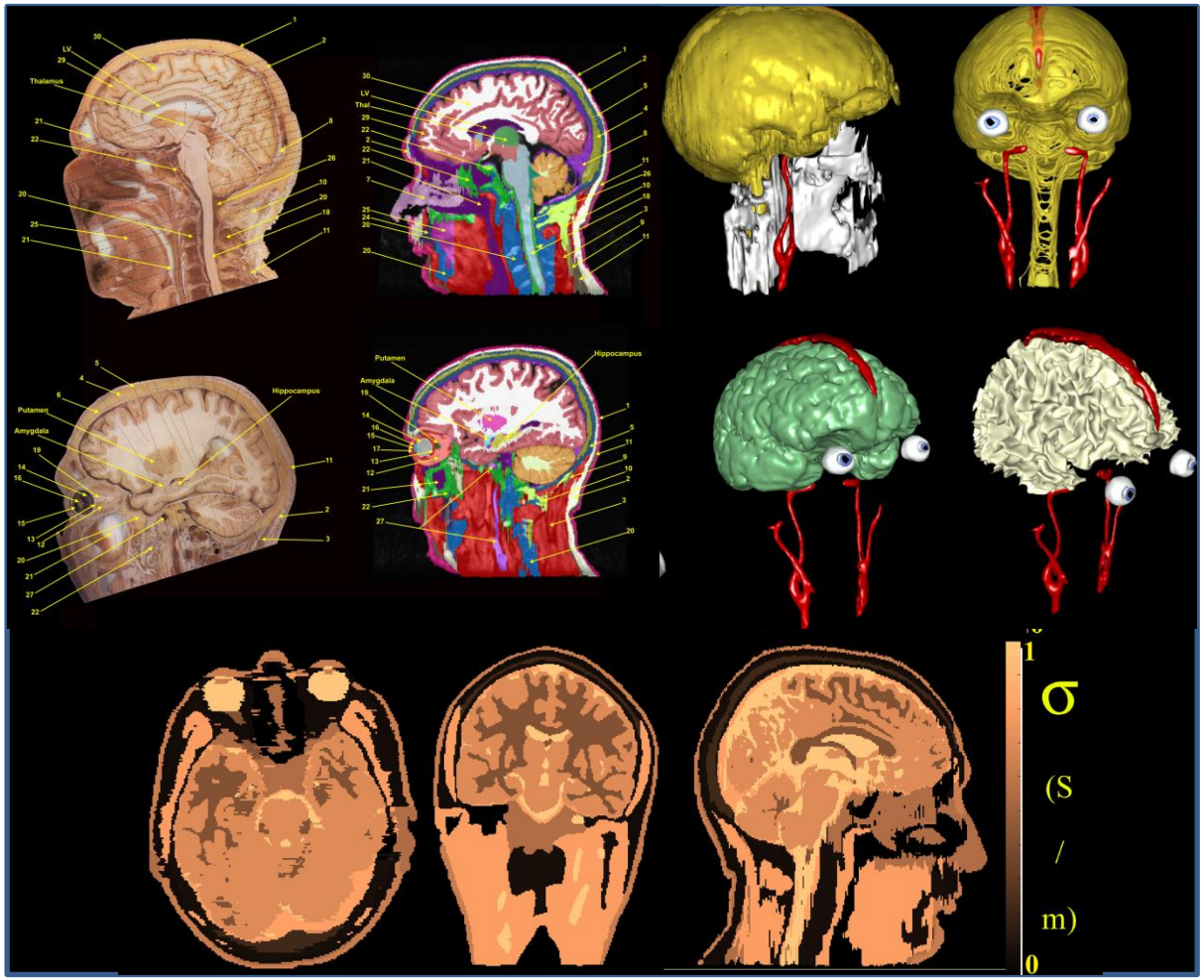
1. Specific Absorption Rate

- ✓ The United States Food and Drug Administration (USFDA) limits the exposure to RF energy SAR < 3.2 W/kg (Head)

$$SAR = \frac{\sigma_c}{2\rho} \left|\vec{E}\right|^2$$

- ✓ Any pulse sequence typically does not raise the temperature by more than 1° Celsius

Human Head Models for EM forward solution



Human Head Model Anatomically accurate with 44-tissues, 1x1x1 mm^3 resolution
(Makris et al., MBEC 2009)

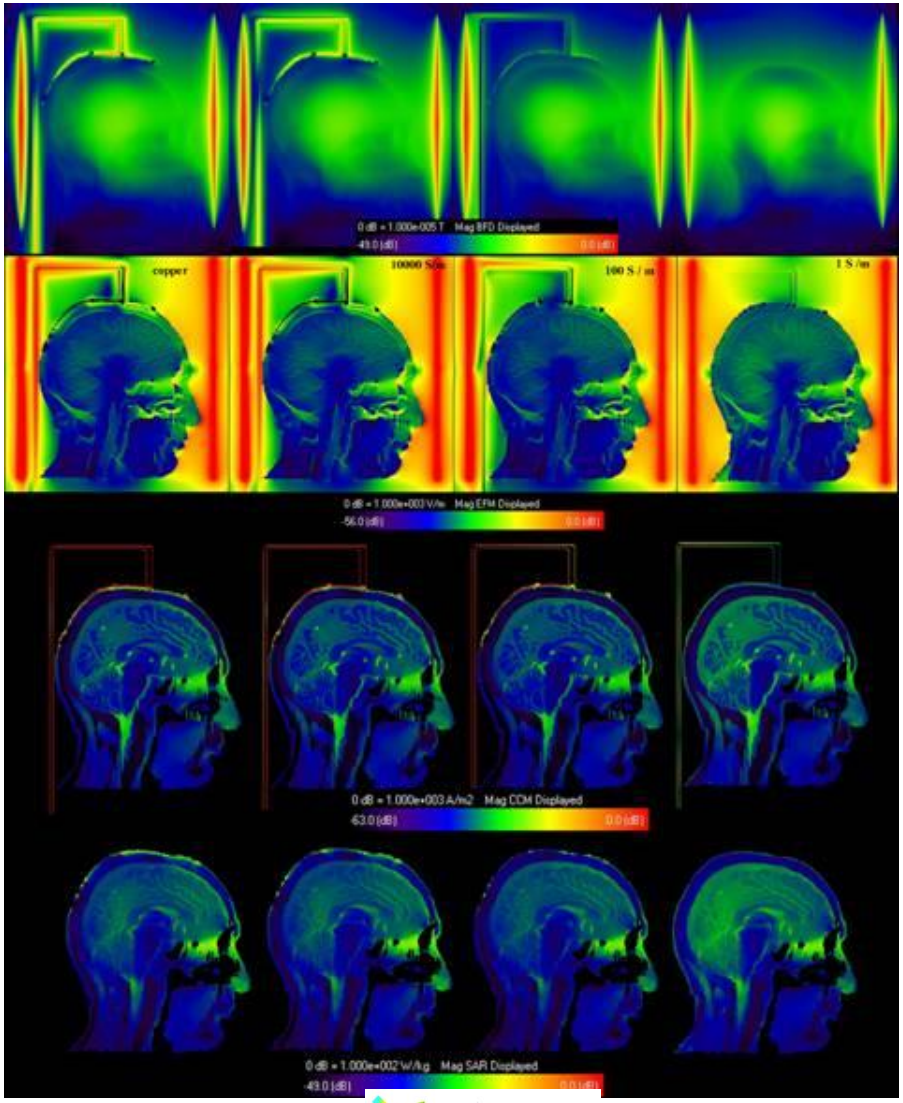
Variable leads resistivity

B field

E field

Induced Currents

SAR



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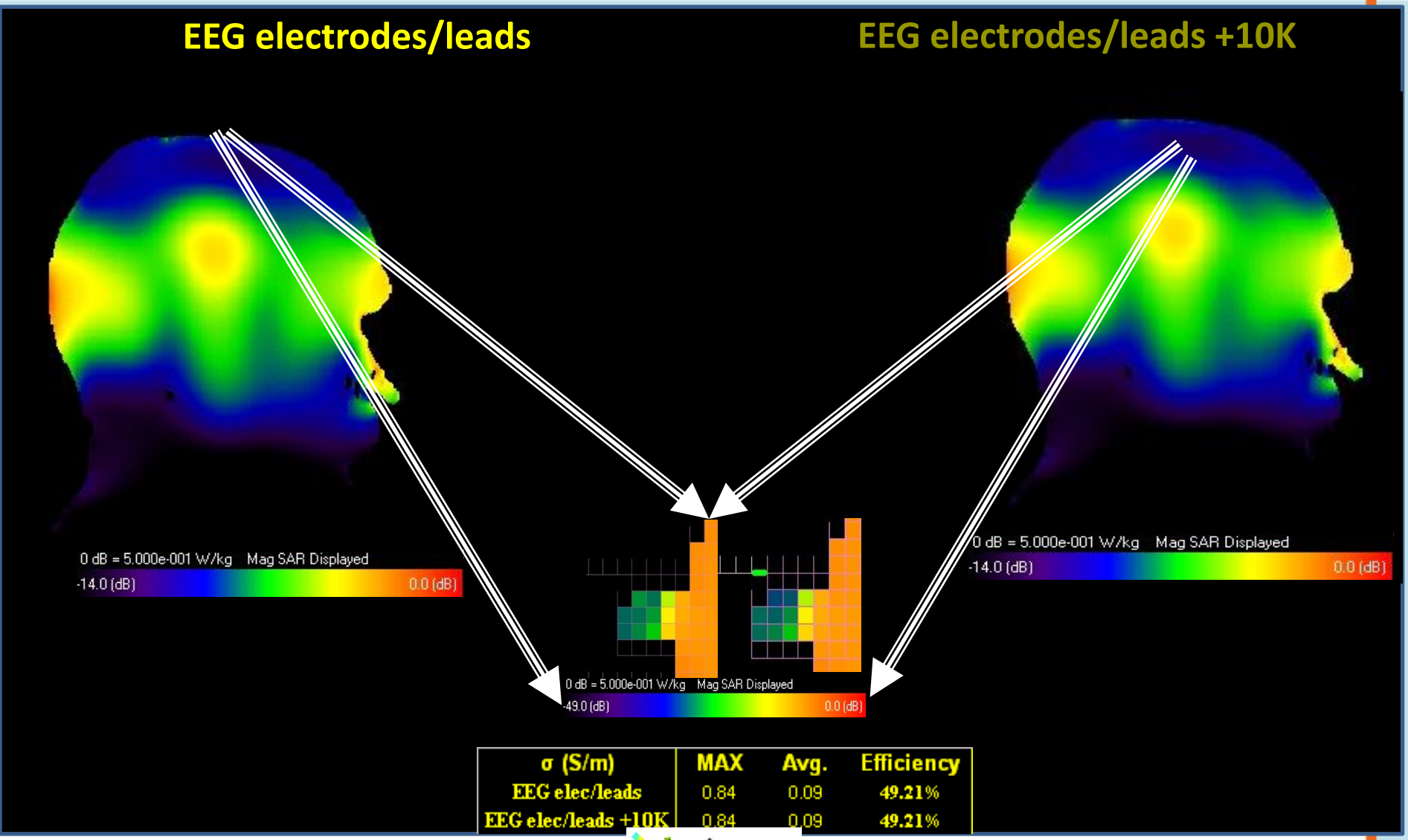
Effects of resistors



σ (S/m)	MAX	Avg.	Efficiency
EEG elec/leads	0.84	0.09	49.21%
EEG elec/leads +10K	0.84	0.09	49.21%

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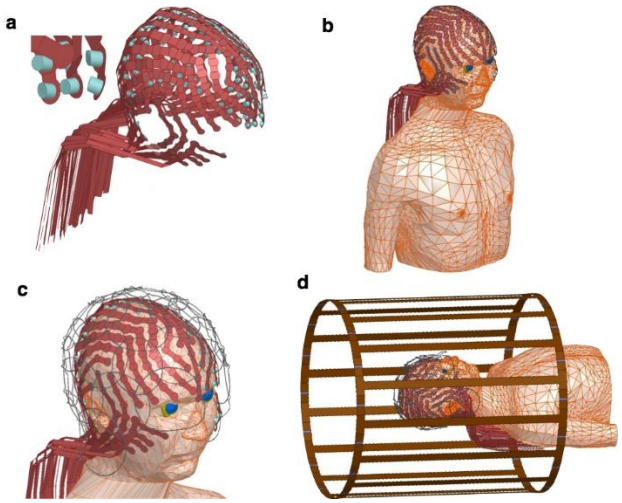
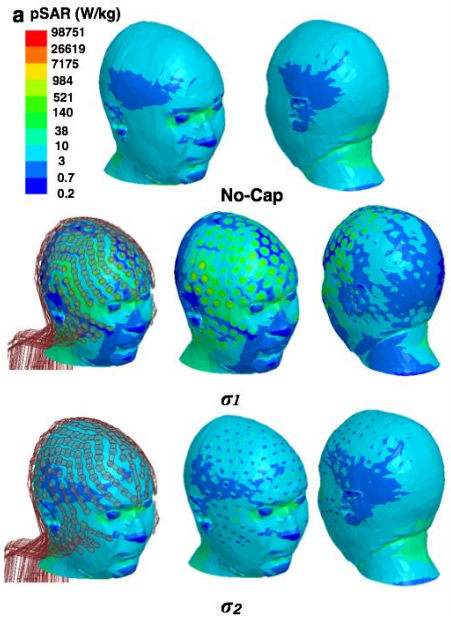
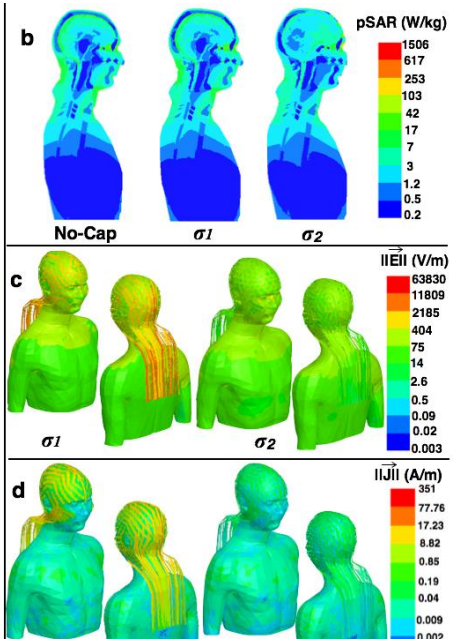
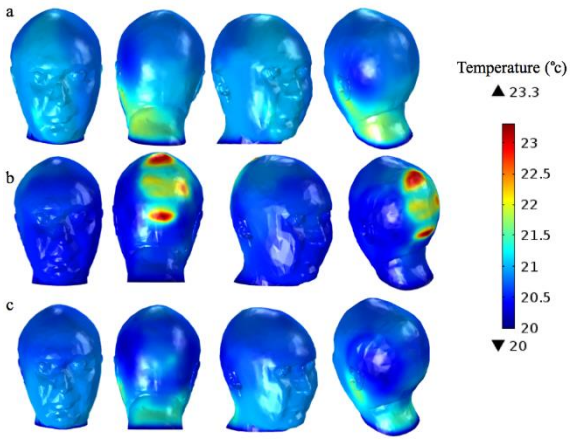
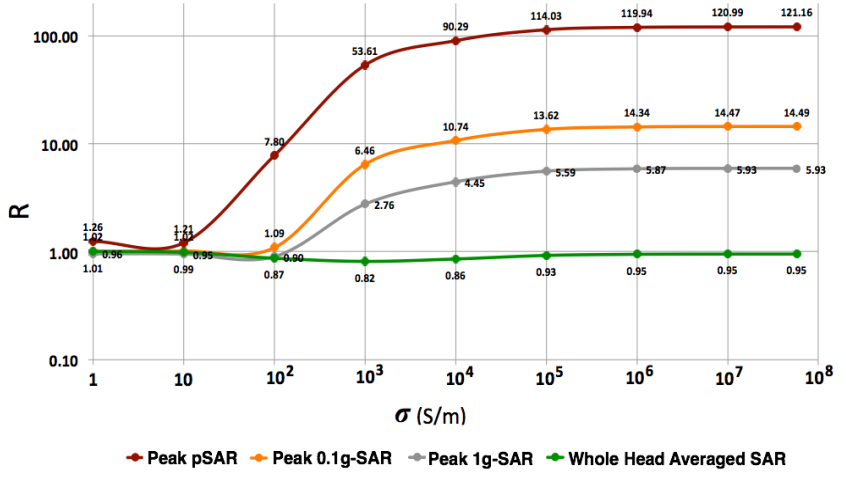
The “InkNet” design











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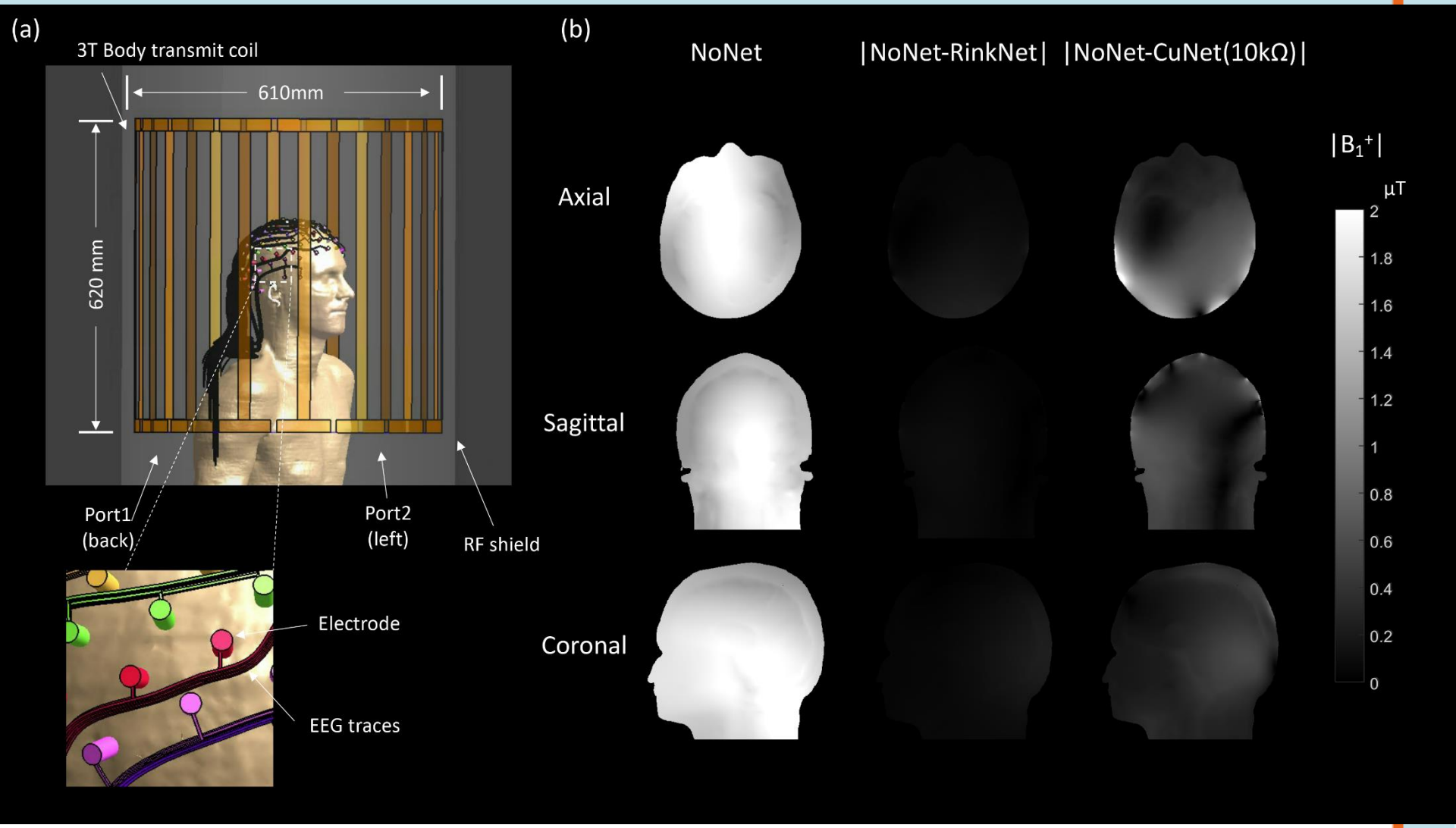
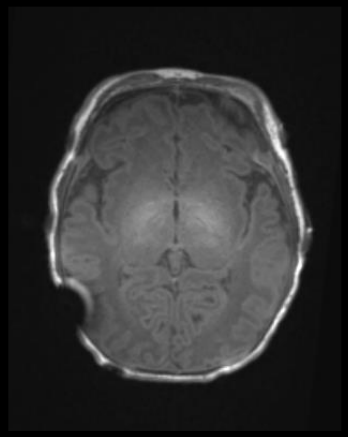
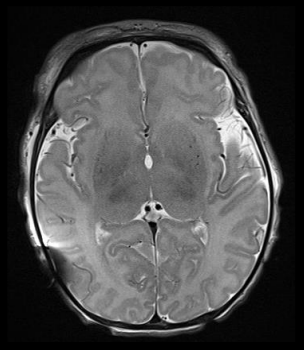
Cloaking @ 3T MRI (Simulations)



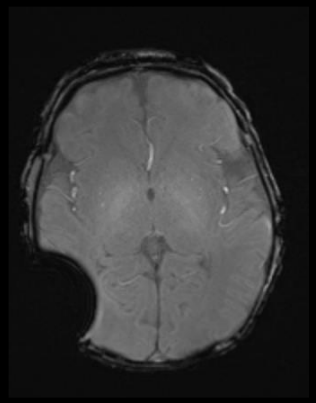
EEG MRI Artifacts @ 3T



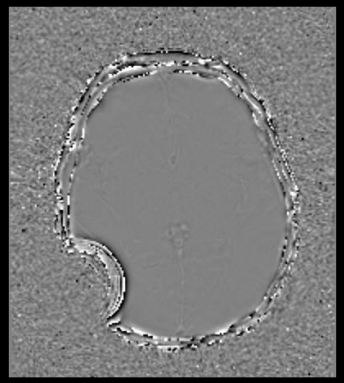
MPRAGE



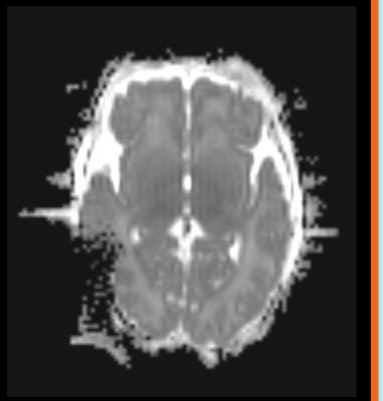
TSE



SWI

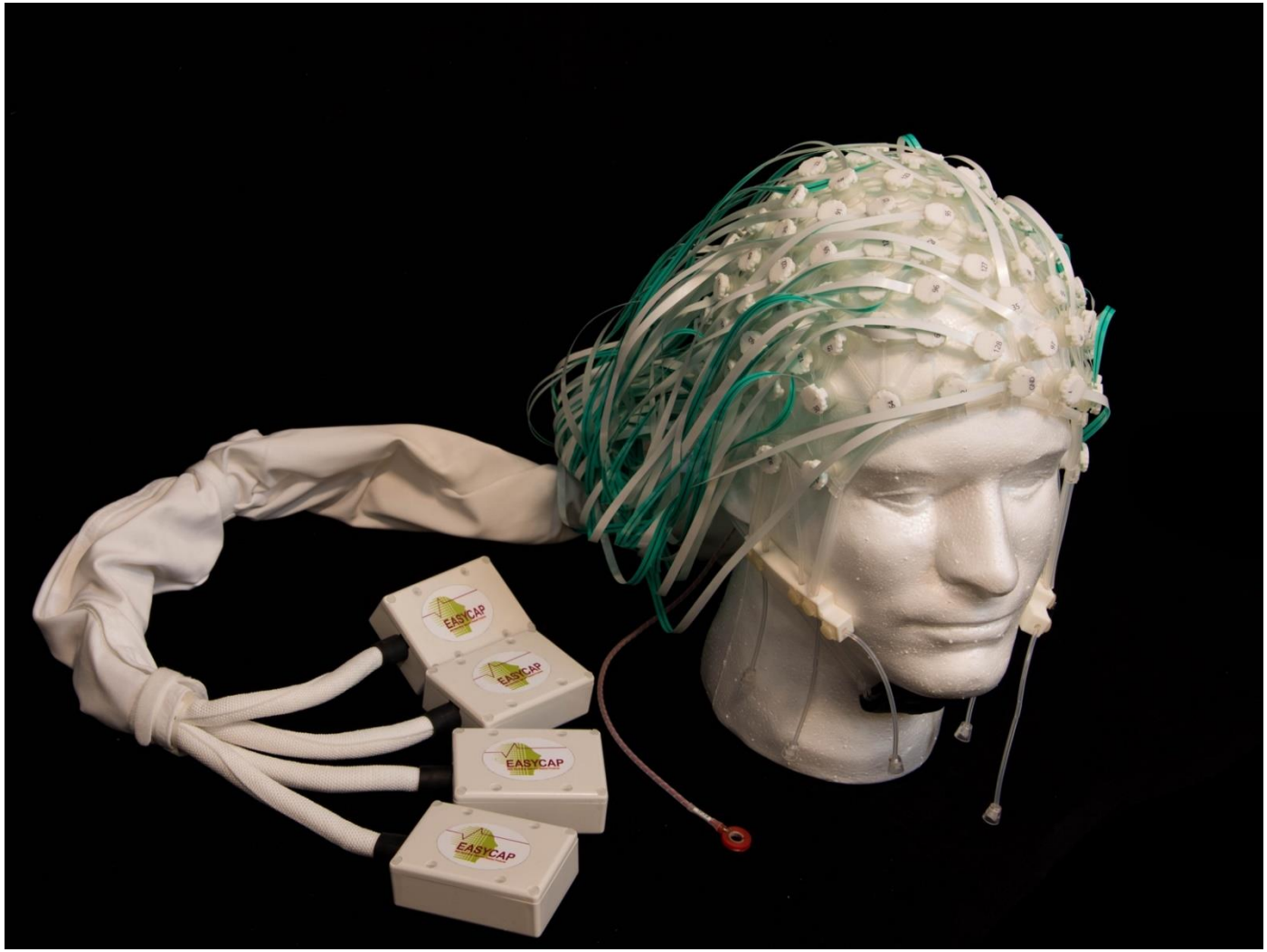


SWI - Phase

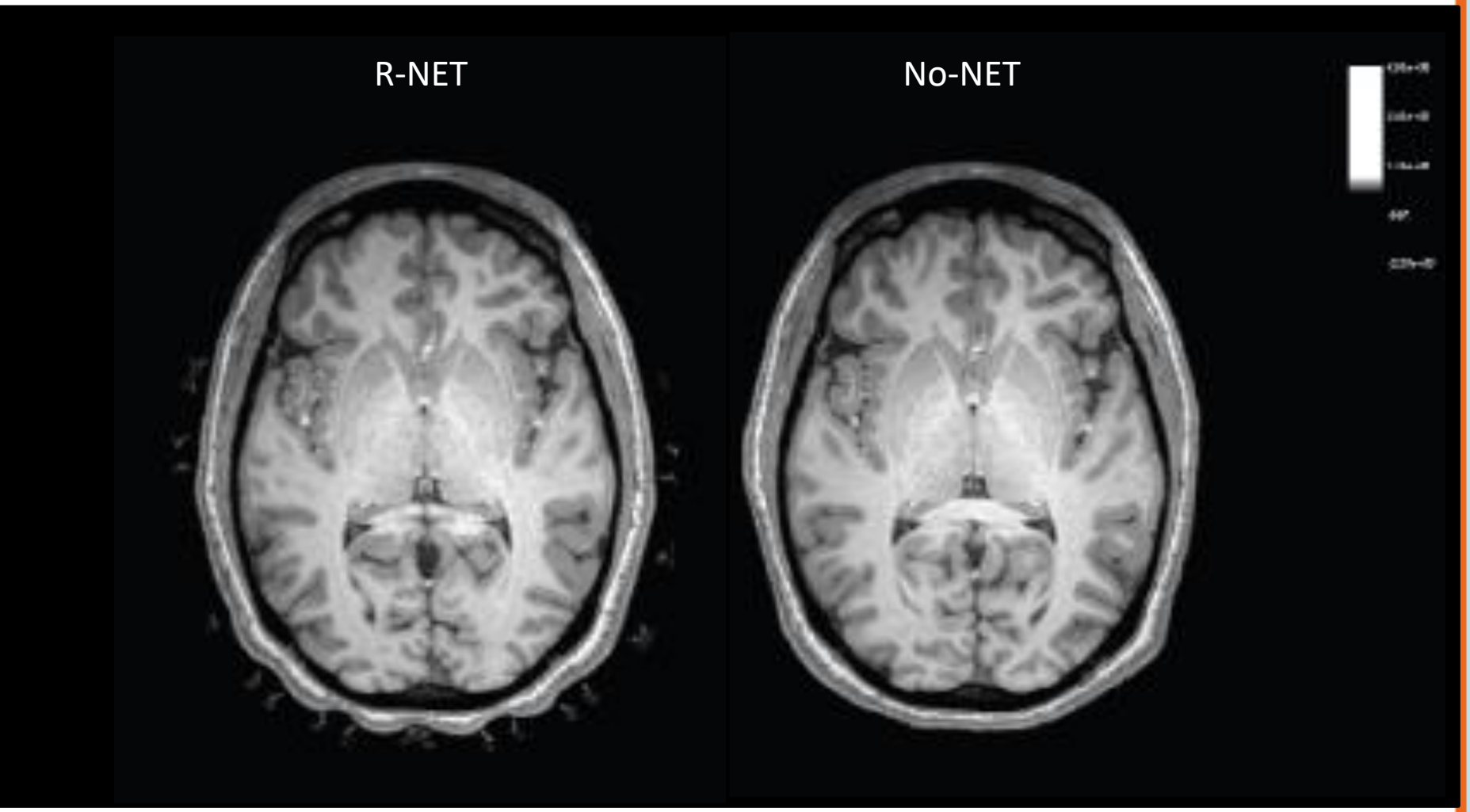


ADC

The R-NET MRI IT

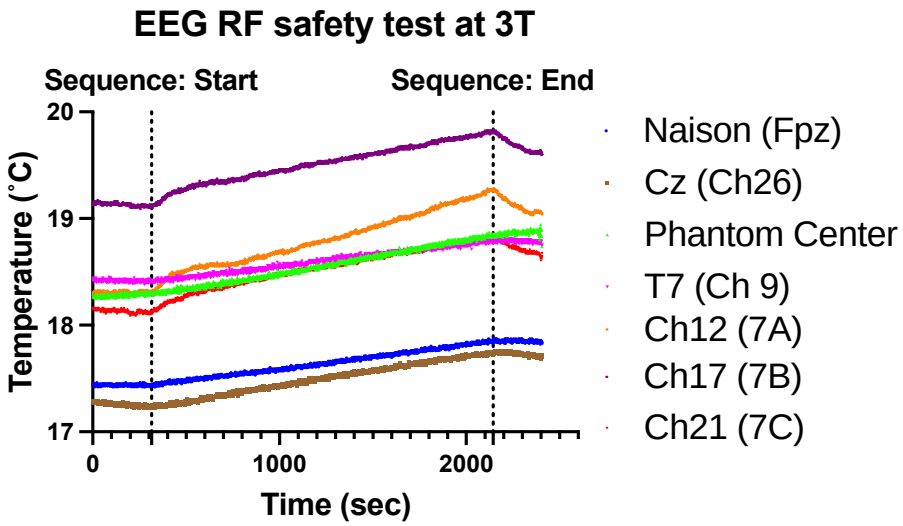


R-Net vs. No Net @ 3T MPRAGE

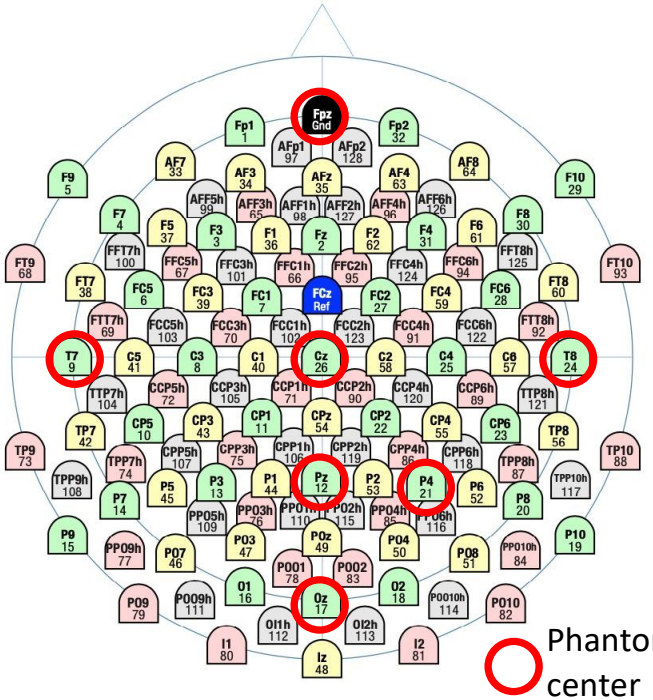


Temperature Measurements at 3T

(a)



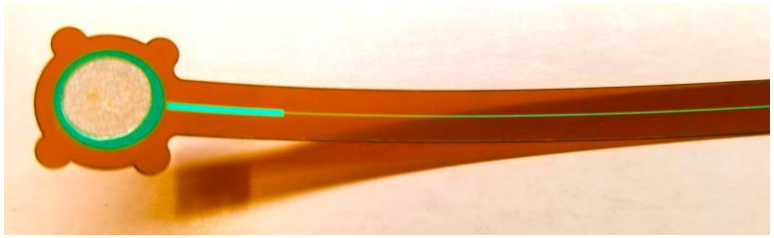
(b)

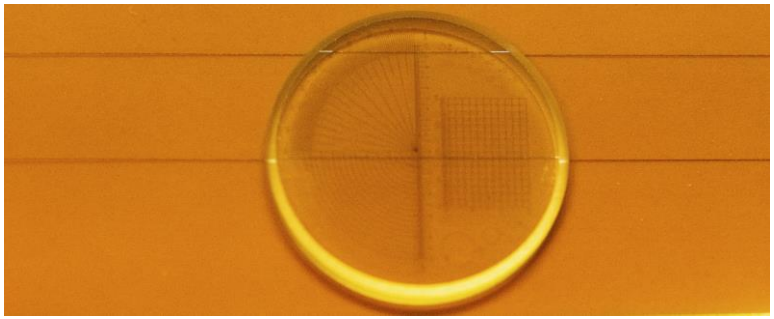


(c)

Time (s)	Fpz (GND)	Cz (Ch26)	Phantom center	T7 (Ch 9)	T8 (Ch 24)	Pz (Ch 12)	Oz (Ch 17)	P4 (Ch 21)
0	17.43	17.24	18.3	18.41	18.93	18.31	19.13	18.13
1828	17.85	17.74	18.83	18.76	19.61	19.27	19.81	18.82
	0.42	0.50	0.53	0.35	0.68	0.96	0.68	0.69

The “NeoNet”





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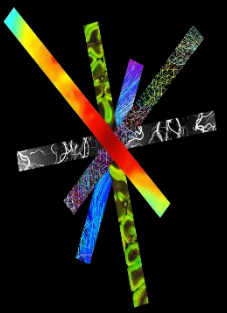
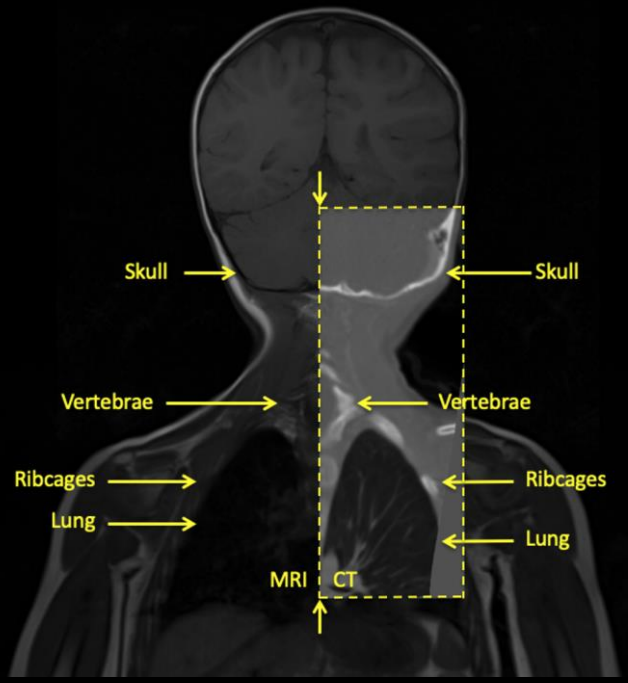
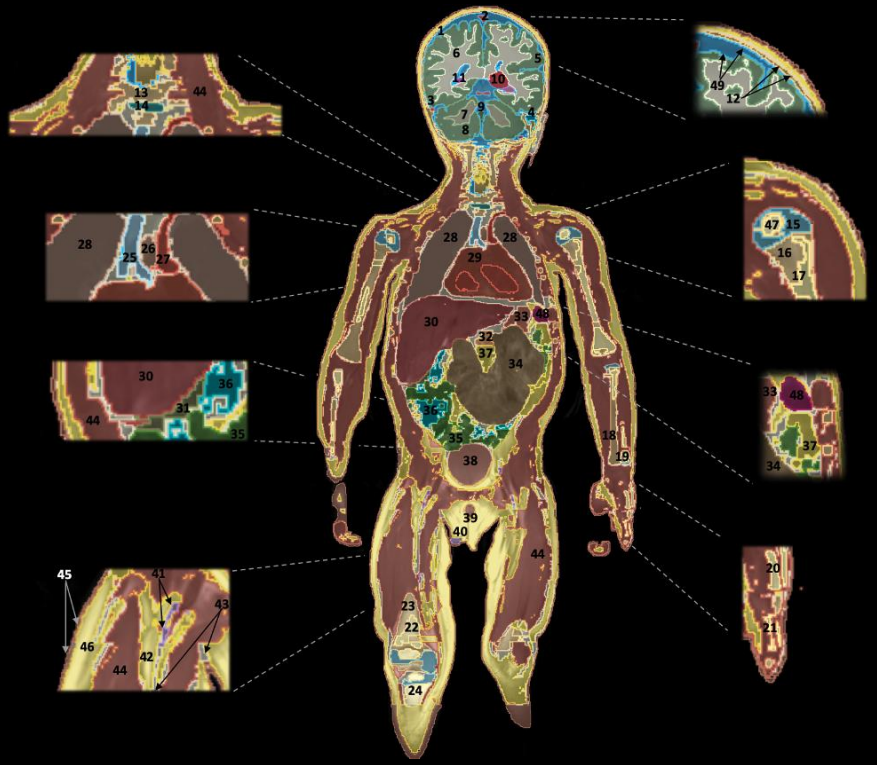


Method: Whole-body segmentation

MARTIN : 29-MONTH-OLD MALE VOXEL MODEL[1]



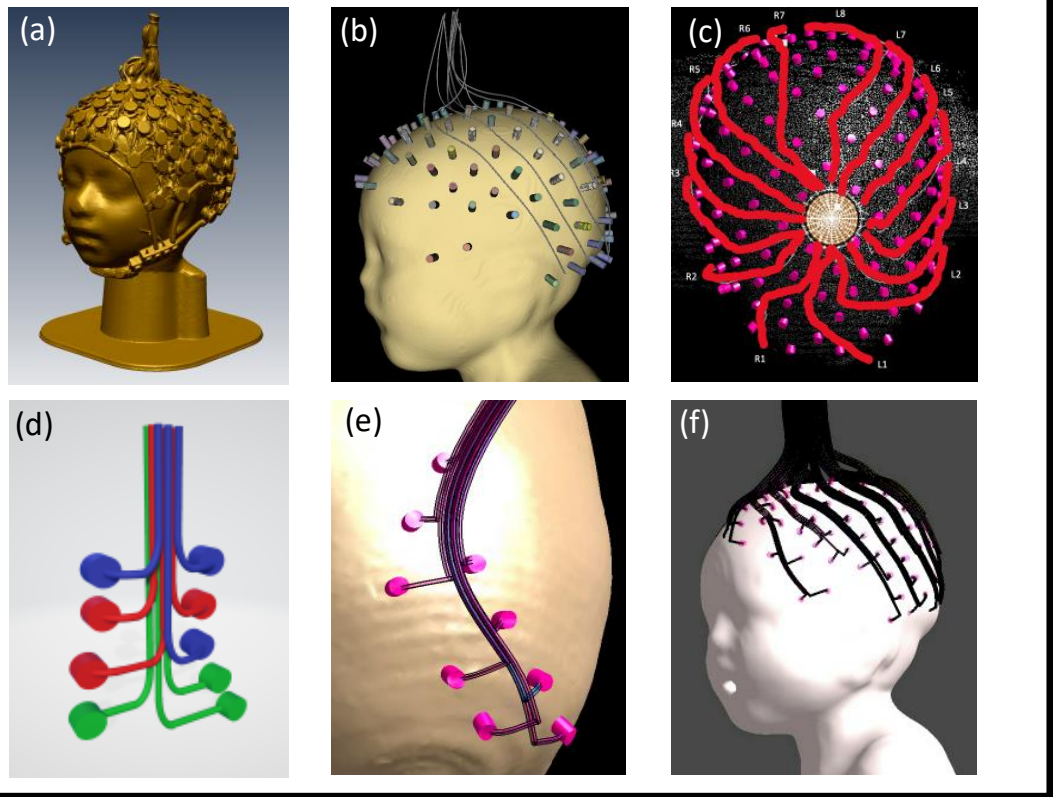
*Available to download the model at https://itis.swiss/martin



Coronal view of the Whole-Body Segmentation

[1] Jeong *et al.*, *PLoS One* 2021;**16**:e0241682c

Methods: Realistic characterization of the EEG traces path[1]



128-channel realistic path of EEG drawing procedure

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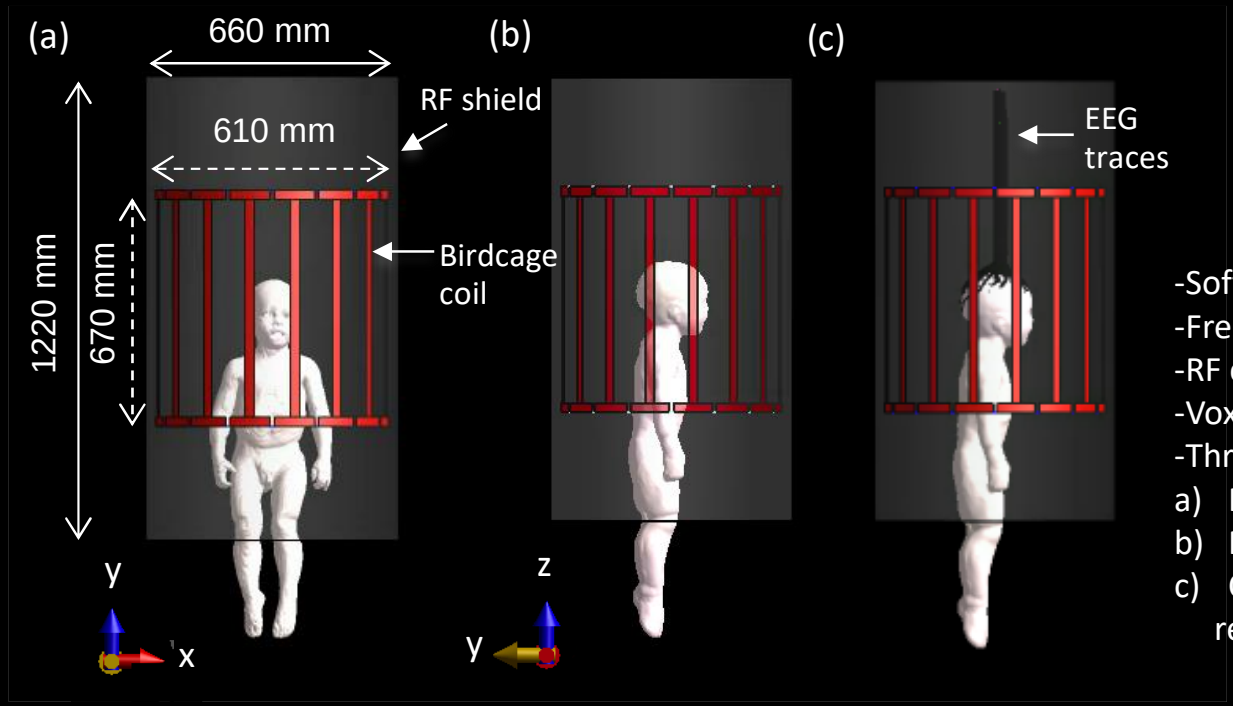
Upper head escaping trace design
(from Brain Products Press Release)

[1] Jeong *et al.*, IEEE Tran Electromag Comp, 63:5 (2021)

Method: EEG-MRI RF safety: Simulation set-up (3T Body transmit coil) [1]



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-Software: Sim4Life (ZMT, Switzerland)
-Frequency: 128 MHz (3T)
-RF coil: Body transmit coil
-Voxel model: MARTIN
-Three simulation condition:
a) NoNet, control (without EEG net)
b) NeoNet (Thin-film resistive trace)
c) Copper Net without current limiting resistors (worst-case scenario)

[1] Jeong *et al.*, IEEE Tran Electromag Comp, 63:5 (2021)

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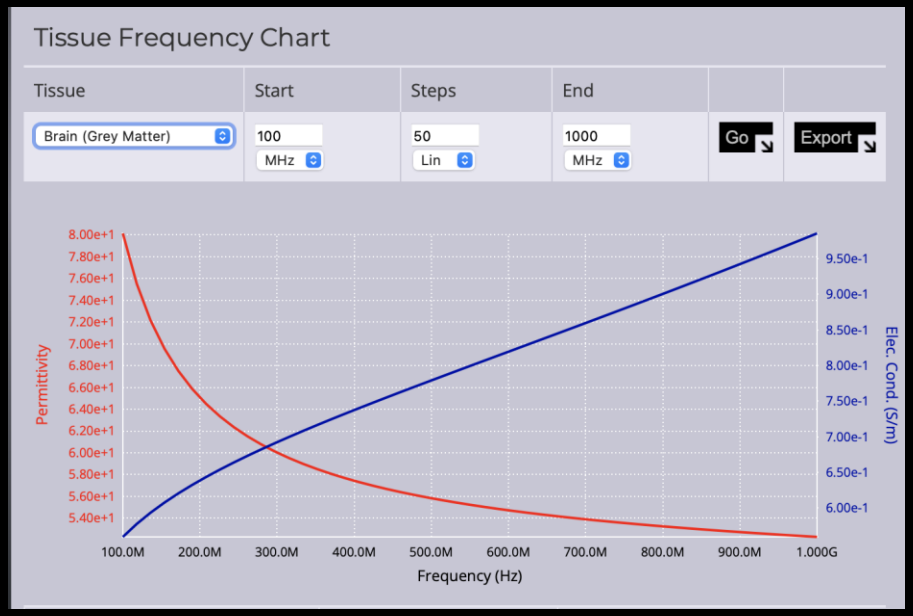
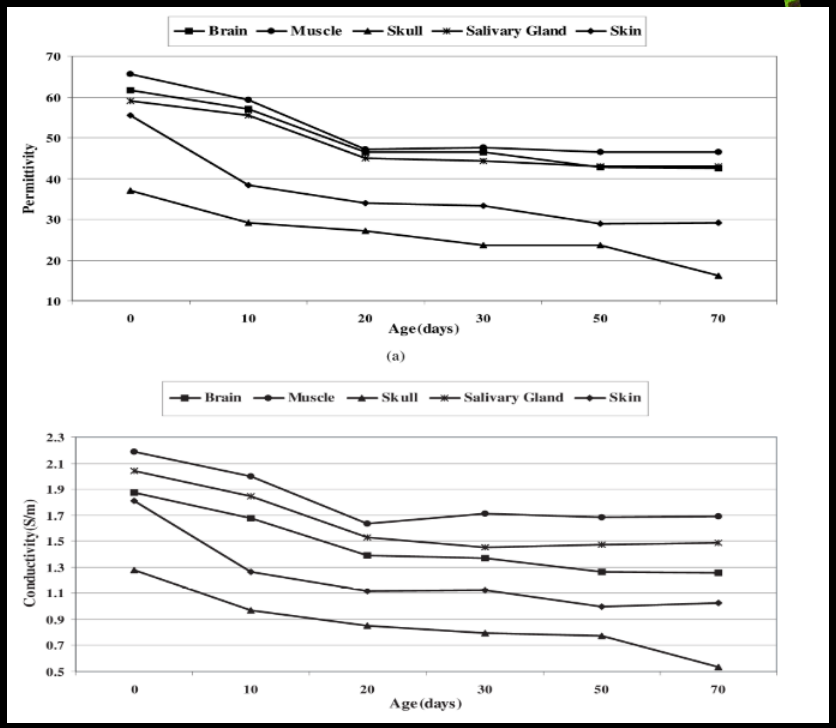
Dielectric properties are frequency dependent [1],[2] + age dependent [3]



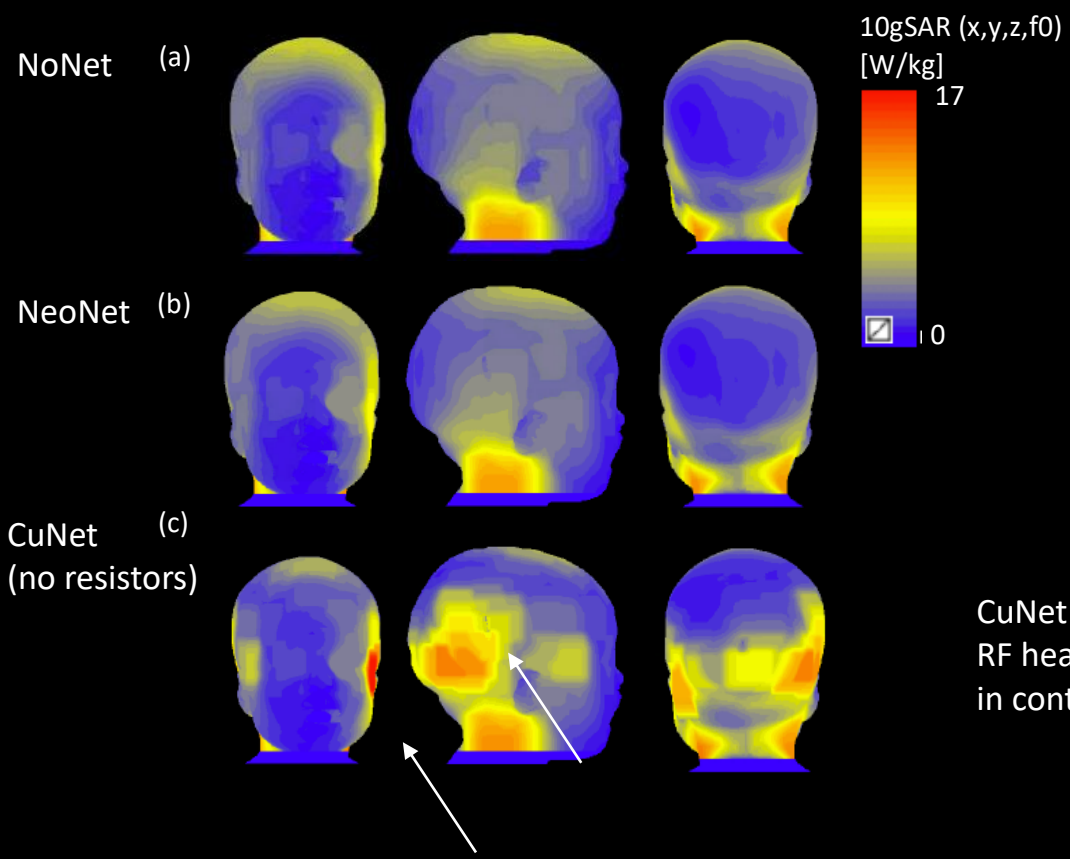
Frequency dependency of permittivity and conductivity of the brain grey matter [1],[2]



Age dependency of permittivity and conductivity [2]

[1] IT'IS database, https://itis.swiss/database, [2] Gabriel *et al.,* (2006) Phy Med Bio, [3] Peyman *et al.*, Phy Med Bio, (2001)

EEG-fMRI RF Safety: 10g-averaged SAR distribution in the worst-case scenario



CuNet shows the potential RF heating areas near the sponges in contact with the skin

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[1] Jeong *et al.*, IEEE Tran Electromag Comp, 63:5 (2021)

Uncertainties analysis to estimate the simulation [1]

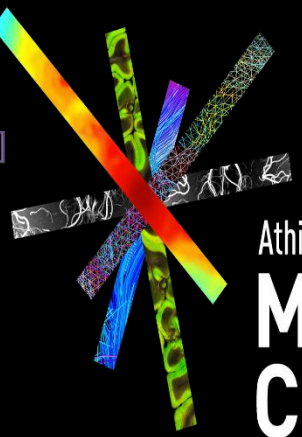

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TABLE II
UNCERTAINTY ANALYSIS (10GSAR)

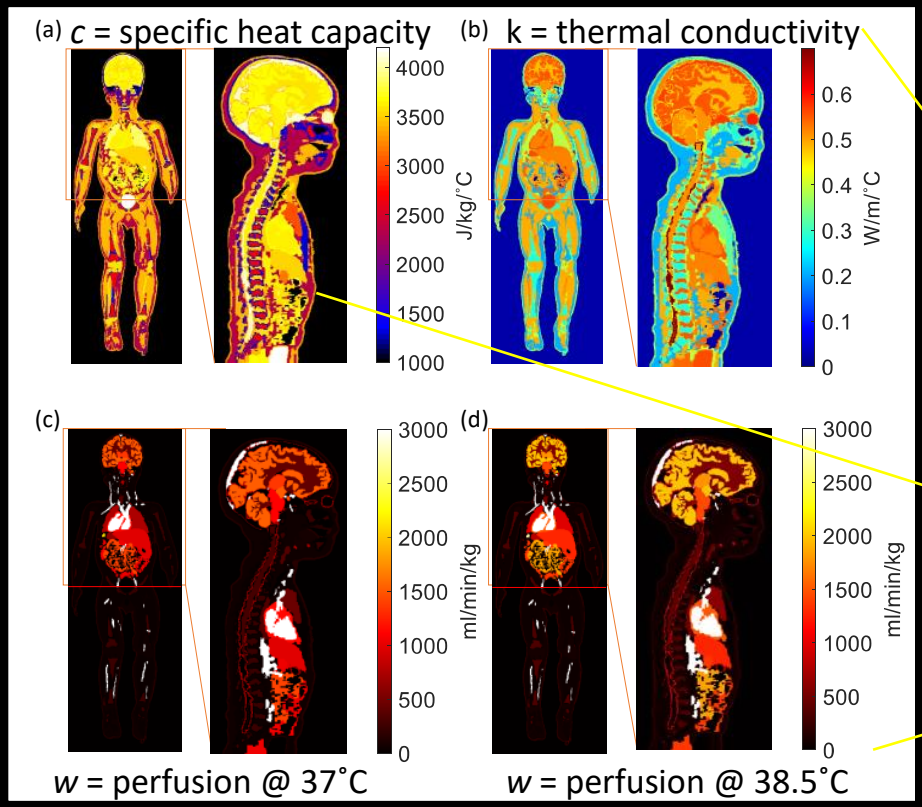
Parameter	QUANTITY EVALUATED	Value 1	Value 2	Result 1 (W/kg)	Result 2 (W/kg)	Sensitivity Factor [%/%]	Std. Dev. [36]	|Uncertainty| (%)
Trace conductivity [S/m]		46.3	50.9	12.52	12.52	0.10E-02	0.04	0.10E-03
		46.3	1.0E+02	12.52	12.52	6.39E-04	0.04	5.66E-05
		46.3	1.0E+03	12.52	14.19	1.34	0.04	0.12
Trace permittivity [-]		4.20	4.62	12.52	12.52	0.10E-03	2.80	0.53E-02
Electrode conductivity [S/m]		2.14	2.35	12.52	12.52	-2.40E-04	0.04	4.59E-04
Electrode permittivity [-]		84.7	93.2	12.52	12.52	0.50E-03	2.80	0.16E-02
Skin conductivity [S/m]	$10gSAR_{max}$ in the head [W/kg]	0.78	0.71	12.52	12.38	-0.11	0.04	0.59
Skin permittivity [-]		84.4	76.0	12.52	12.46	-4.69E-02	2.80	0.16
Subcutaneous fat conductivity [S/m]		0.10	0.09	12.52	12.45	-5.37E-02	0.04	2.25
Subcutaneous fat permittivity [-]		15.1	13.6	12.52	12.43	-7.28E-02	2.80	1.35
Muscle conductivity [S/m]		1.01	0.91	12.52	11.95	-0.46	0.04	1.87
Muscle permittivity [-]		74.9	67.4	12.52	12.39	-0.10	2.80	0.38
Coil position x [mm]		0.0	10.0	12.52	11.72	-0.64	1.15	0.73
Coil position y [mm]		0.0	10.0	12.52	14.71	1.75	1.15	2.01
Coil Position z [mm]		0.0	10.0	12.52	12.91	0.31	1.15	0.36
Total Uncertainties	9.83 %							

The methods used were based on the work of Neufeld et al. [36] to evaluate the uncertainty of the quantities derived by simulation, two simulations were assessed for each parameter by assigning two different values ("Value 1" and "Value 2"). The first value ("Value1") was the one used for the simulation shown in ***Fig. 6****, whereas the second value ("Value2") was set across 10% changes in dielectric properties (e.g., tissue properties were adjusted towards adults' tissue properties) and 10 mm shift of the coil position in three directions to gauge their impact on the simulation results of* $10gSAR_{max}$ [36]*. The results obtained for each value ("Result1" and "Result 2") were used to evaluate the sensitivity factor of the quantity evaluated of* $10gSAR_{max}$*. The measurement standard deviation ("Std. Dev.") was derived from literature values* [36].

- Estimate the simulation sensitivity by varying the simulation parameters (e.g., conductivity, permittivity) by 10 %

[1] Neufeld et al., 2010, Phy Med Bio, [2] Jeong *et al.*, IEEE Tran Electromag Comp, 63:5 (2021)

Thermal parameters using in thermal simulation



Thermal properties of child tissue [2],[3]

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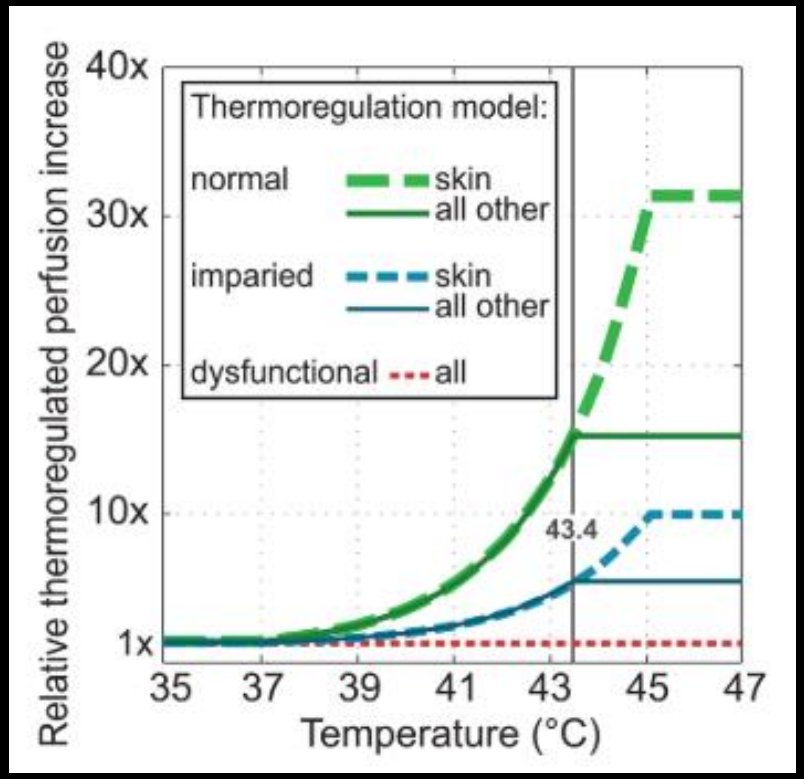
- Pennes' bioheat equation [1]

$$(\rho c)_t \frac{\partial T_t}{\partial t} = \nabla \cdot (kT_t) + \rho Q + \rho SAR - \rho_b c_b \rho \omega (T_t - T_b)$$

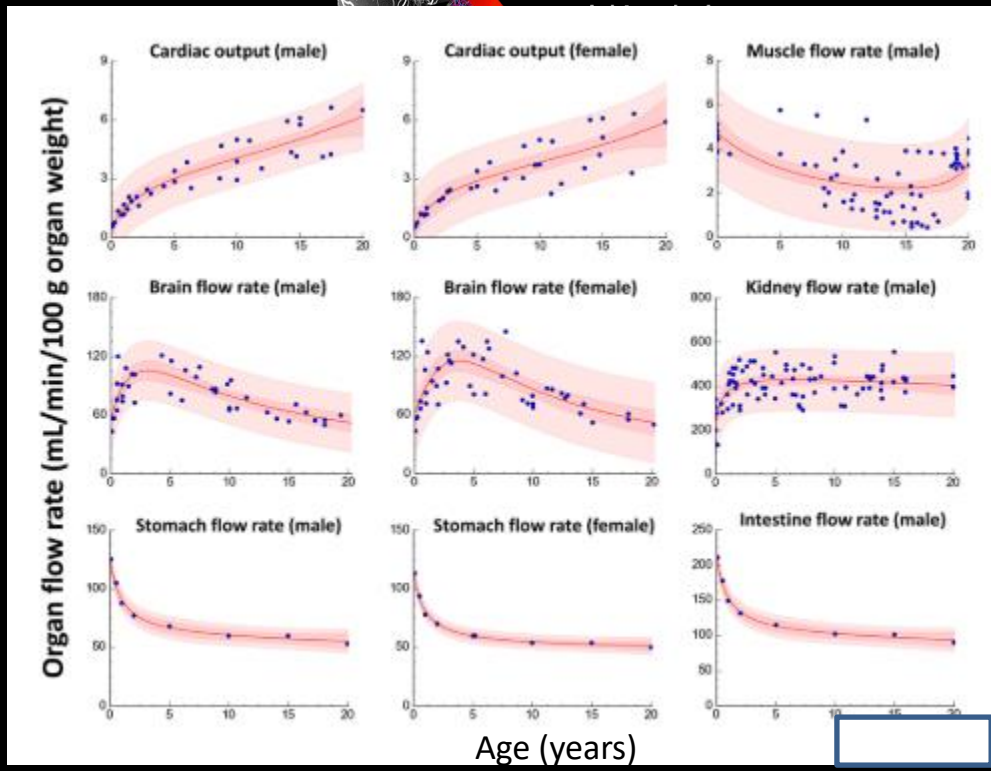
ρ: mass density of the tissue (ρ_b = blood density)
Q: metabolic heat generation rate
c_b: specific heat capacity of the blood
T_t: Temperature of the tissue (T_b: blood temperature)
t: time

[1] H. Pennes, Jour appl Physio (1948), [2] Jeong *et al.*, IEEE Tran Electromag Comp, 63:5 (2021), [3] IT'IS database, https://itis.swiss/database,

Tissue perfusion rate (temperature dependency, and age-dependency)



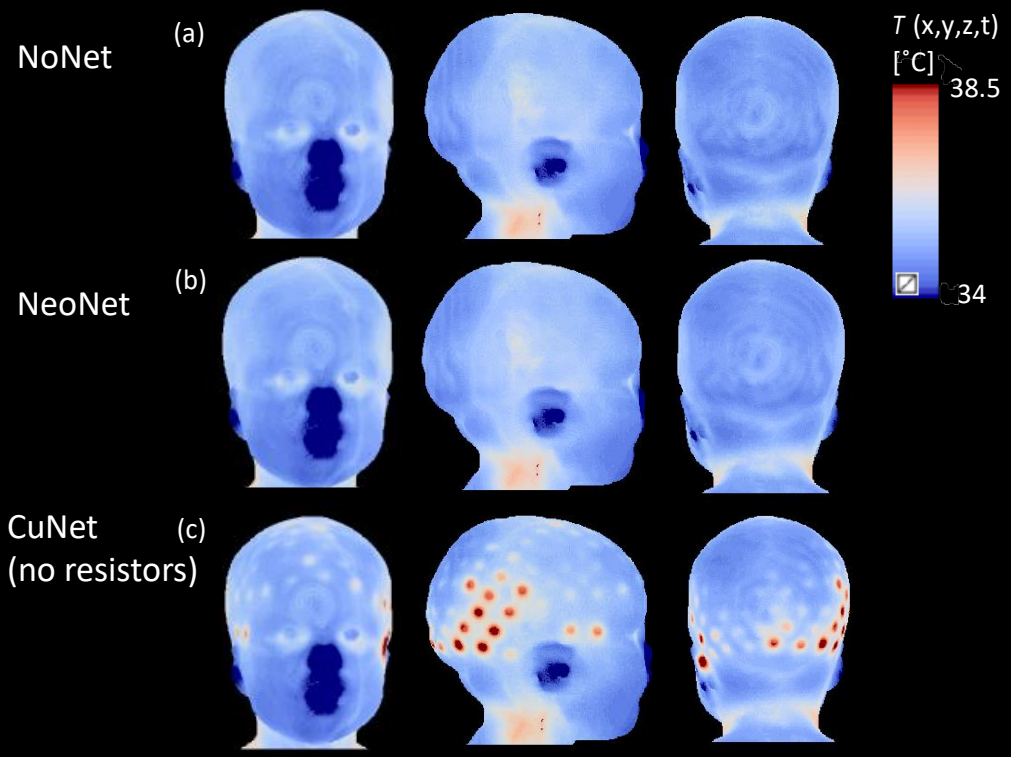
Thermal dependency on perfusion rate



Age-dependency on perfusion rate

[1] Murbach *et al.*, MRM, 76:3(2016), [2]Chang et al, The APPS Journal (2021)

Results: Thermal simulation [1]



Thermo-regulated perfusion simulation results in the worst-case scenario (3.2 W/kg in the head) for 15 minutes of continuous scan.

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[1] Jeong *et al.*, IEEE Tran Electromag Comp, 63:5 (2021)

Conclusions

A. EEG-fMRI was devised for epilepsy presurgical planning for medically refractory epilepsies.
B. Multimodal Imaging (MRI, PET, SPECT, MEG, EEG) is widely used in clinical Epilepsy.
C. A new clinical trial (Jackson in Australia) is showing an increase of 17% in number of potential candidates.
D. Presented new High Density EEG Net for Adults and Pediatric use.
E. Illustrated the design procedures and manufacturing approaches.
F. Showed the MRI and CT cloaking ability of the two Nets.
G. Will HD-EEG and pediatric EEG be part of IEEE P2010?

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Acknowledgements

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