Peripheral Nerve Stimulation (PNS) Analysis of MRI Head Gradient Coils with Human Body Models

Yihe Hua* [(1)], Desmond T.B. Yeo [(1)], and Thomas KF Foo [(1)]

(1) GE Global Research, Niskayuna, USA, 12309,

e-mail: {yihe.hua, yeot, thomas.foo}@ge.com

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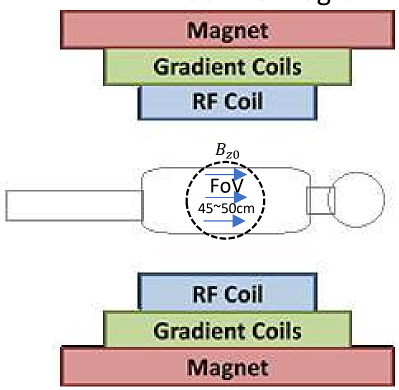
Overview

- Background
  - MRI Gradient Coil and Peripheral Nerve Stimulation(PNS)
  - Head Coil vs. Whole Body Coil
- Coupled Electromagnetic-Neurodynamic Method for Gradient Coil Analysis
  - Shortcomings of Yoon-sun Nerve Trajectory Model for Head Gradient Coil PNS Analysis
  - Add Nerves to Yoon-sun/Duke Model and Verification on Two MRI Head X Coils
  - Gradient Coil Design of Non-folded and Folded Coils
  - PNS by Non-folded and Folded Coils in Yoon-sun
  - Impact to PNS Calculation with Homogenous/Simplified Tissue Properties
- Conclusions

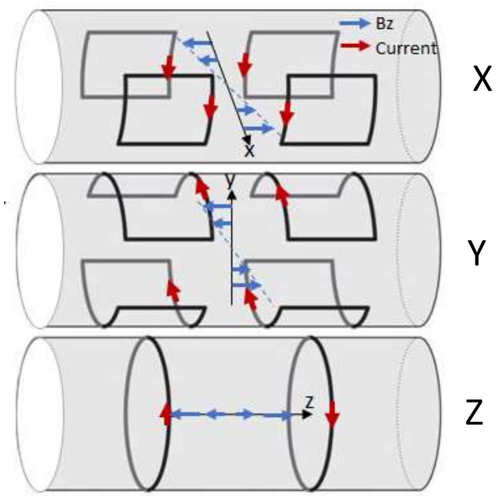
MRI Gradient Coil and E-field

MRI Machine Diagram

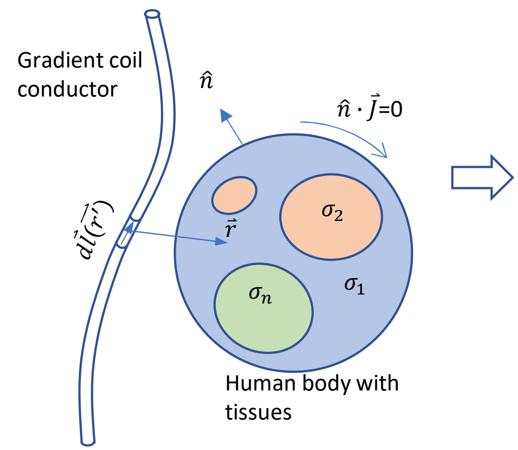


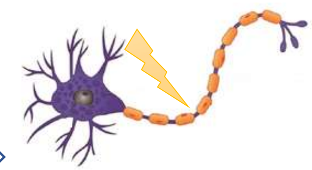
Main components in MRI machine

Three Gradient Coils



E field in Human Body





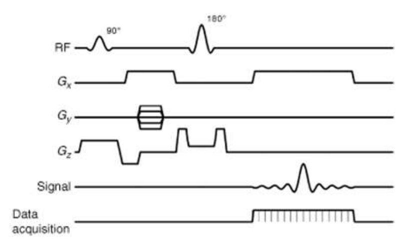
Peripheral Nerve Stimulation (PNS)

<u>Magnet</u>: main Bz0 (1.5T, 3T, etc.)
<u>Gradient coil</u>: a linear Bz field
<u>RF coil</u>: transmit/receive RF signal

Gradient coil: Spatial encoding.
Proton(H) spin resonance frequency

$$\omega = \gamma Bz$$
$$= \gamma\left(B_{z0} + xG_x + yG_y + zG_z\right)$$

In modern MRI machine, <u>alternative pulse sequences</u> are applied for each gradient coil such that RF signals with multiple frequencies and phases are generated and the 3D space information of the subject can be recovered by utilizing Fourier Transform.



$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \nabla\varphi$$

where

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi}\int_l \frac{I(\vec{r}')}{|\vec{r}-\vec{r}'|}\, d\vec{l}(\vec{r}')$$

with $\nabla \cdot \vec{J}$=0 and $\vec{J} = \sigma\vec{E}$, get

$$\nabla \cdot \sigma\nabla\varphi + \nabla \cdot \sigma\frac{\partial \vec{A}}{\partial t}=0$$

Boundary condition

$$\hat{n} \cdot \vec{J}=0 \rightarrow \frac{\partial\varphi}{\partial n} + \hat{n} \cdot \frac{\partial \vec{A}}{\partial t} = 0$$

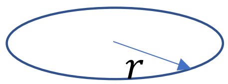
Sim4Life is used for FEM simulation

Head vs. Whole Body Gradient Coil

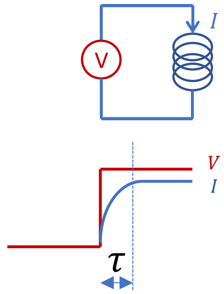
A rough estimation on E-field intensity from B

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\oint_l \vec{E} \cdot d\vec{l} = \frac{\partial}{\partial t}\int_A \vec{B} \cdot d\vec{s}$$



$$E(r) \sim \frac{r \partial B}{2 \partial t}$$

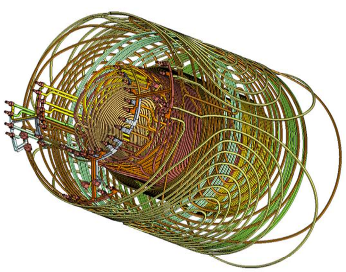


$$V = L\frac{dI}{dt} + RI$$

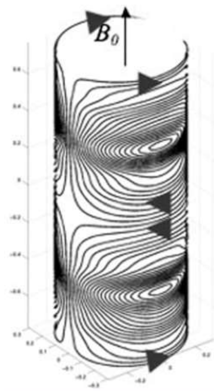
$$B, G \propto I$$

Slew Rate(SR)=$\partial G / \partial t$

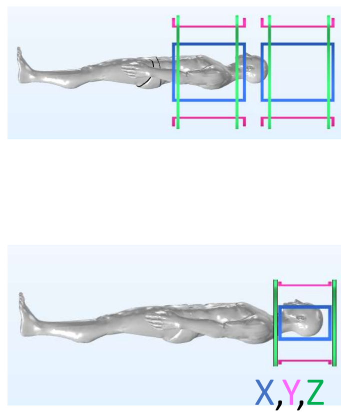
Gradient coil	Needs	Characters
Typical Whole-Body Gradient	cover the whole body, reasonable resolution	big FoV(45~50cm) big Coil, G=30~50mT/m, SR=100~200T/m/s
Head Gradient	cover the brain, microstructure, neuroimaging, high resolution, fast	small FoV(26cm) MAGNUS: G=200mT/m, SR=500T/m/s [1] HG2: G=85mT/m, 700T/m/s[2]

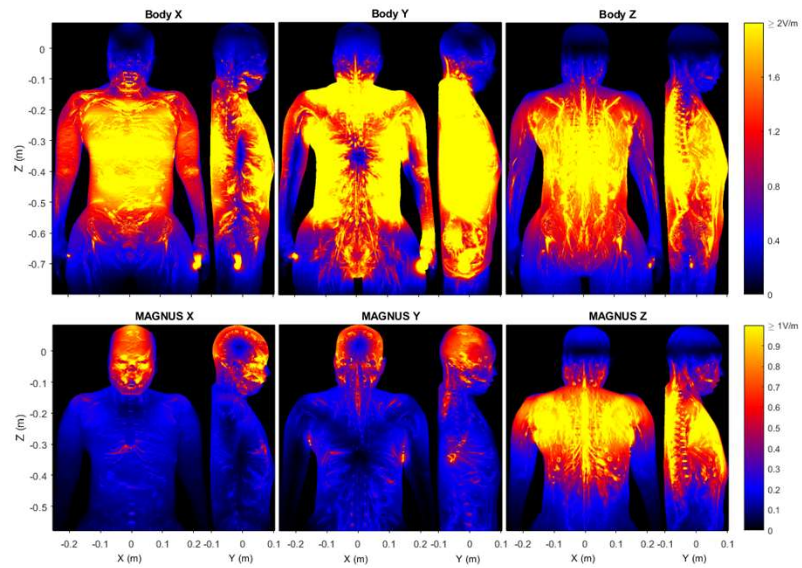


MAGNUS



Typical Whole-Body X/Y Gradient Coil Primary layer[3]





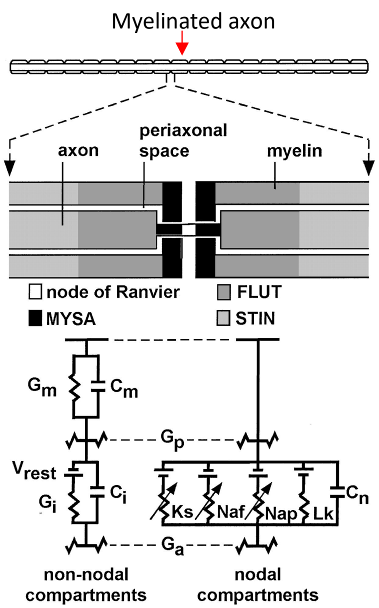
|E| field projected on XZ and YZ plane in Yoon-sun model by a Typical Body Gradient and MAGNUS (scaled to 100T/m/s)

[1]T. K. F. Foo et al., Highly efficient head-only magnetic field insert gradient coil for achieving simultaneous high gradient amplitude and slew rate at 3.0t (MAGNUS) for brain microstructure imaging, MRM, vol. 83, pp. 2356–2369, 2020.

[2] T. K. F. Foo et al., Lightweight, compact, and high-performance 3 T MR system for imaging the brain and extremities, MRM, Vol.80, pp. 2232–224, 2018

[3]Hidalgo-Tobon, S. Theory of gradient coil design methods for magnetic resonance imaging. Concepts Magn. Reson., 36A: 223-242, 2010

Neurodynamic Simulation



McIntyre-Richardson-Grill Axon Model [1]

Action potential propagation can be described by cable theory equation[2]:

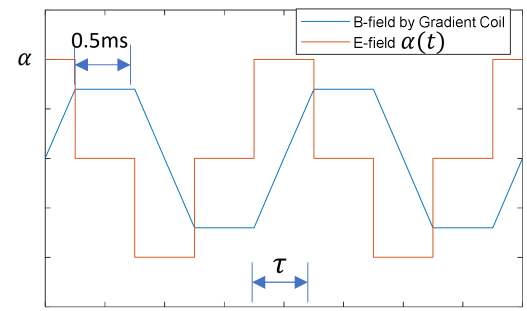
$$C_m \frac{dV_n}{dt} + G_m V_n - G_a(V_{n-1} - 2V_n + V_{n+1}) = G_a\left(V_{e,n-1} - 2V_{e,n} + V_{e,n+1}\right) \leftarrow \frac{\Delta E_l}{\Delta l}$$

V_n: membrane potential minus resting potential
$V_{e,n}$: extracellular potential
G_m: membrane conductance
C_m: membrane capacitance
G_a: axial internodal conductance
G_m is further controlled by membrane potential reflecting the transient on-off status and the current-conducting ability of the sodium channel, potassium channel and other paths on the membrane.

With $\vec{E}$ calculated in human body from the previous step
$E_l = \vec{E} \cdot \hat{l}$
where l is each nerve trajectory

$$V_e = \int_l E_l \, dl$$

Real $V_e(t) = V_e \cdot \alpha(t) \cdot T$
where $\alpha(t)$ is time domain modulation function and T is the additional scaling coefficient.



Titration process:
For each nerve trajectory, $V_e(t)$ is iteratively scaled until an action potential is initialized, then
$\Delta G = SR_0 \cdot \alpha \cdot \tau \cdot T$

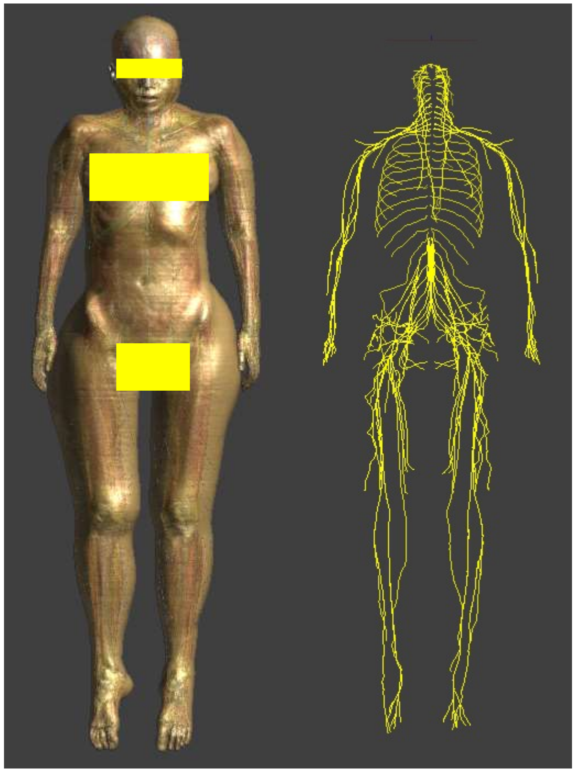
neuron model	MRG
diameter(um)	16(motor)
	12(sensory)
τ(ms)	0.2,0.5
Platue Time(ms)	1

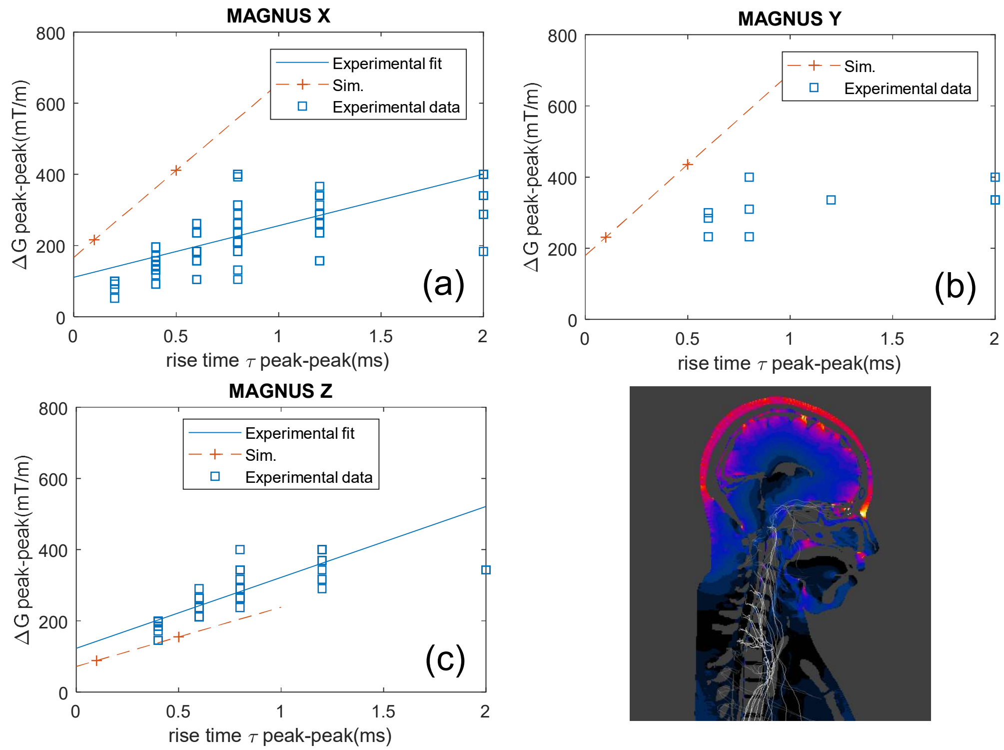
NEURON is used for neuron simulation

[1]Cameron C. McIntyre, et al., Modeling the Excitability of Mammalian Nerve Fibers: Influence of Afterpotentials on the Recovery Cycle, J Neurophysiol 87: 995–1006, 2002
[2]D. R. McNeal, Analysis of a model for excitation of myelinated nerve, IEEE Trans. Biomed. Eng, vol. 23, pp. 329–337, 1976.

Yoon-sun Nerve Model

Yoon-sun model w/ 929 nerve trajectories



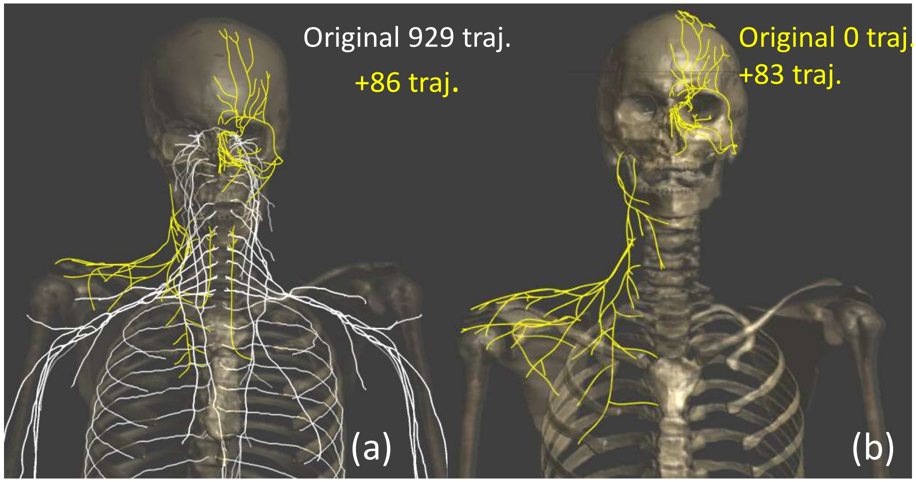


PNS simulation vs. measurement on MAGNUS[1]

- Original Yoon-sun(IT'IS foundation, ver4.0b03) nerve model results for MAGNUS show discrepancies for X/Y coils due to the fact it lacks extracranial nerve trajectories in Yoon-sun model.

[1] Y Hua, DTB Yeo, TKF Foo ,PNS Estimation of a High Performance Head Gradient Coil by a Coupled Electromagnetic Neurodynamic Simulation Method, 50th European Microwave Conference (EuMC), 2021

Add Nerves to Yoon-sun and Duke Model



(a)Yoon-sun: Original nerve traj.(White), +86 nerve traj.(Yellow)[1]
(b)Duke: +83 nerve traj.

Added nerves
Buccal branch of left facial
Temporal branch of left facial
Lateral brach of left supraorbital
Medial branch of left supraorbital
Left supratrochlear
Left infratrochlear
Left recurrent laryngeal
Right recurrent laryngeal
Right dorsal scapular
Right medial supraclavicular
Right accessory
Cervical branch of right facial nerve

- Only part of extracranial and superficial neck/shoulder nerve trajectories were added, due to the symmetry of human body and difficulties in CAD modelling, to cover the X coil shinning region. Z coil PNS result has been explained by original nerves in Yoon-sun; Y coil has not been covered in this study.

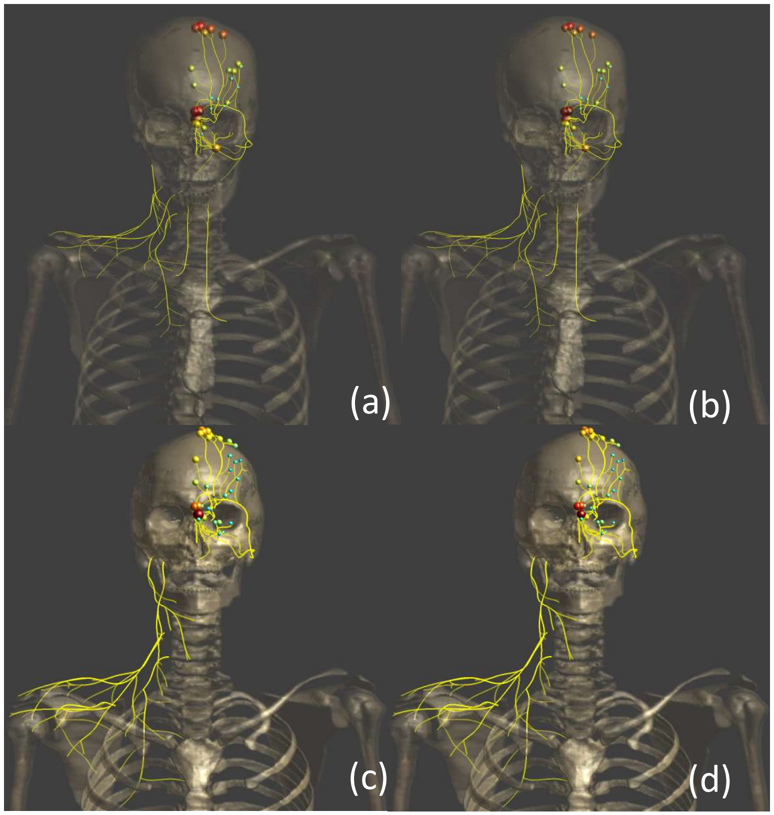
[1] Y Hua, DTB Yeo, TKF Foo , PNS Analysis on Folded and Non-folded Gradient Coil Designs with a Coupled EM-Neurodynamic Simulation Method, ICEAA2021: abstract 323

PNS results on Yoon-sun and Duke Model

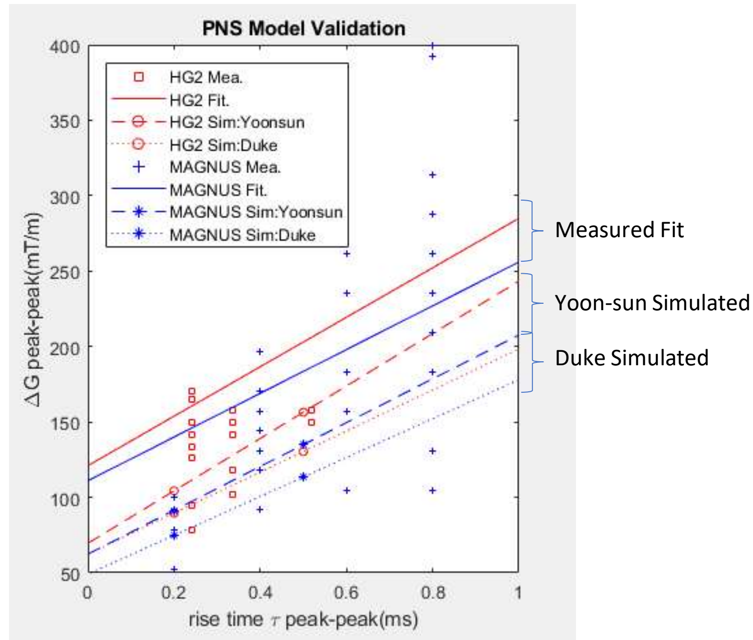
MAGNUS HG2

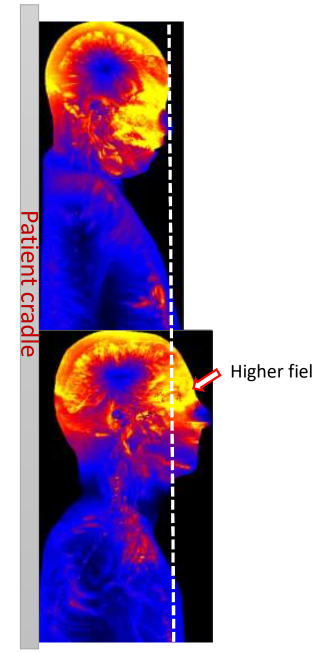
Yoon-sun

Duke



Most sensitive places for PNS

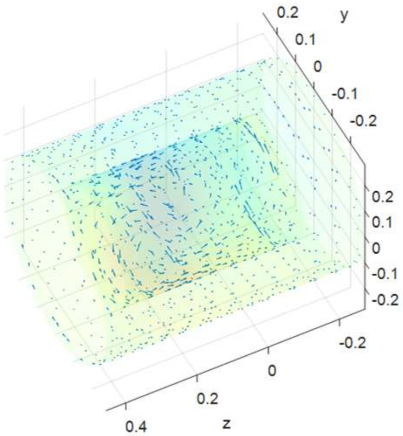




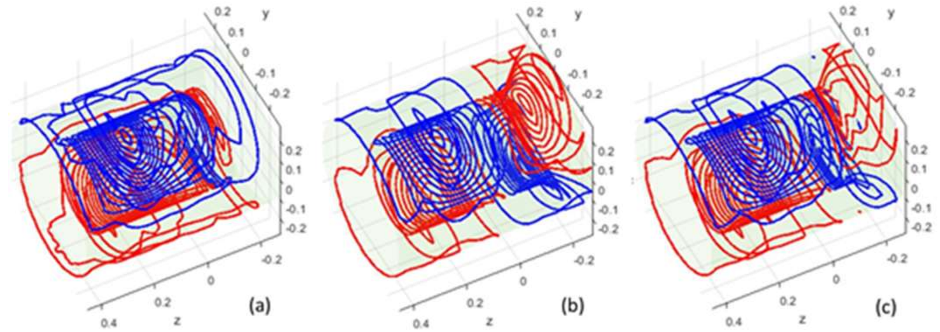
- Much better agreement achieved for PNS after using additional nerve trajectories(nasion/glabella and forehead[1]);
- Lower threshold in Duke than in Yoon-sun due to the model size[2];
- Overestimation(simulated PNS threshold lower than measurement) observed, probably due to the end effects[3].

[1] E. T. Tan et al., Peripheral nerve stimulation limits of a high amplitude and slew rate magnetic field gradient coil for neuroimaging, MRM, 83(1),352–366, 2020.
[2] M. Davids et al., Prediction of peripheral nerve stimulation thresholds of MRI gradient coils using coupled electromagnetic and neurodynamic simulations, MRM, 81,686-701,2019
[3] Y Hua, DTB Yeo, TKF Foo ,PNS Estimation of a High Performance Head Gradient Coil by a Coupled Electromagnetic Neurodynamic Simulation Method, 50th European Microwave Conference (EuMC), 2021

Gradient Coil Design: Non-folded and Folded Coils



Current density : $\vec{J} = \sum c_i \vec{f_i}$



Coil A
Non-folded

Coil B
Folded

Coil C
Folded and limit turn numbers on connection region

Magnetic energy: $E_B = \frac{1}{2} L I^2 = \frac{1}{2} \int_V \int_V \frac{\vec{J}(\vec{r}) \cdot \vec{J}(\vec{r}')}{r^2} dr dr' = \frac{1}{2} c^T \mathcal{L} \, c$

→ Quadratic form

Field: $B_z(\vec{r}) = \frac{\mu_0}{4\pi} \left(\int_V \frac{\vec{J}(\vec{r}') d\vec{l}(\vec{r}') \times (\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3} \right)_z = \mathcal{B}_z c$

Force, torque, eddy current, PNS.... → Linear form

primary length(cm)	50.4	D_FOV (cm)	24
shield length(cm)	72.6	Offset of FOV center to coil geometry center (cm)	-9.2
TS length(cm)	137	current(A)	400
D_primary(cm)	33.6	gradient Strength(mT/m)	60
D_shield(cm)	55.8	ε (max field error in FOV)	10%
D_TS(cm)	90.6	λ(max field error by eddy current)	0.2%

Optimization Problem:

To find: $c = [c_1, c_2, \ldots, c_n]^T$

Minimize: $\frac{1}{2} c^T \mathcal{L} \, c$, or other quadratic form

Constraint: $G_x x - \mathcal{E} \leq \mathcal{B}_z c \leq G_x x + \mathcal{E}$

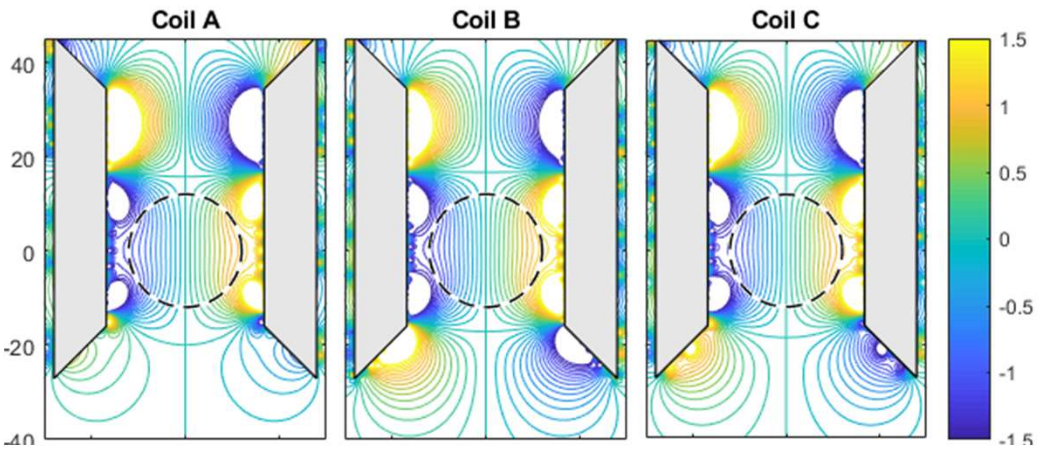
Force: $\mathcal{F}_z c \leq F_0$

etc.

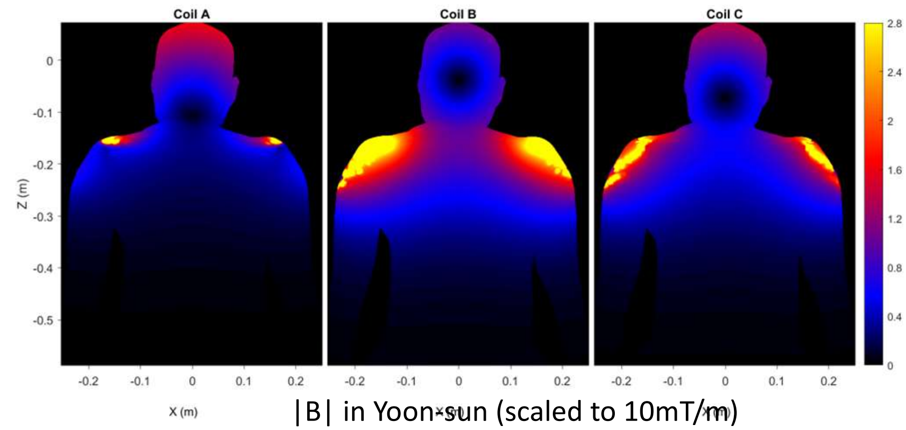
- Parameter setup follows [1,2] to maximize the efficiency
- PNS constraint[3] is not directly applied in this design

[1] Fangfang Tang et al. An improved asymmetric gradient coil design for high-resolution MRI head imaging, Phys. Med. Biol. 61 8875, 2016
[2] Y Hua, DTB Yeo, TKF Foo. Analysis of Peripheral Nerve Stimulation in Asymmetric Non-folded and Folded Head Gradient Coil Design, ISMRM 2020: No.4236
[3] M. Davids, B. Guérin, V. Klein and L. L. Wald, "Optimization of MRI Gradient Coils With Explicit Peripheral Nerve Stimulation Constraints," in *IEEE TMI*, 40(1)129-142, 2021

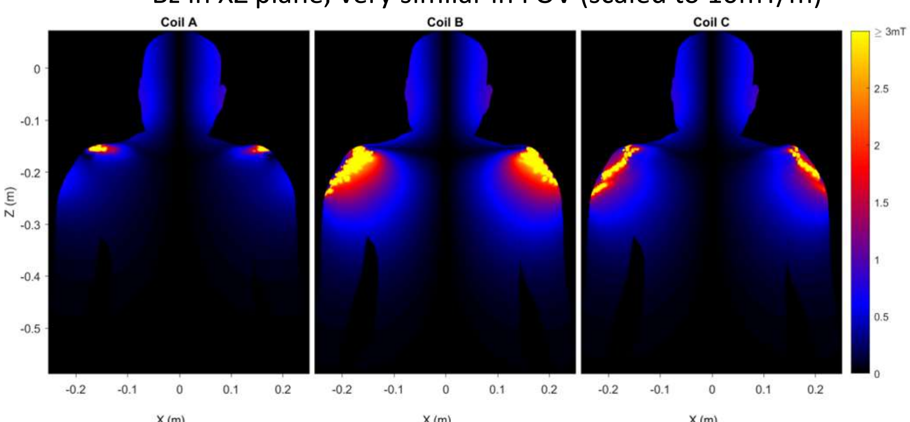
B field and |E| of the Three X Coils



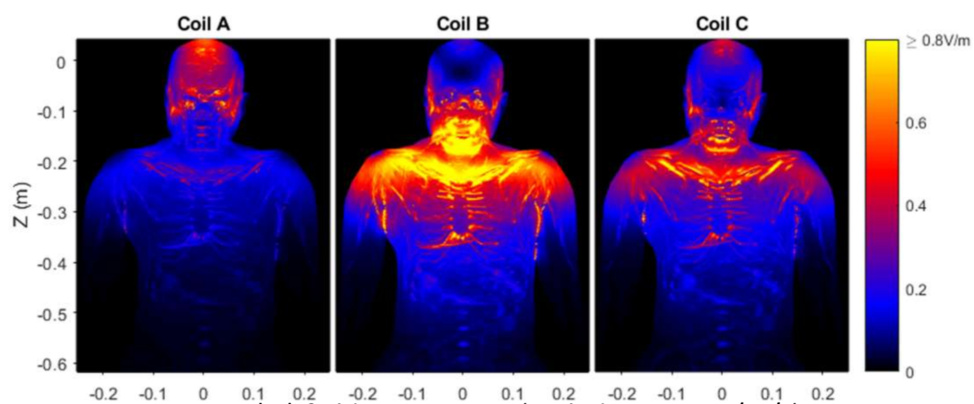
Bz in XZ plane, very similar in FOV (scaled to 10mT/m)



|B| in Yoon-sun (scaled to 10mT/m)



Bz in Yoon-sun, similar in head, but different in shoulder/chest (scaled to 10mT/m)



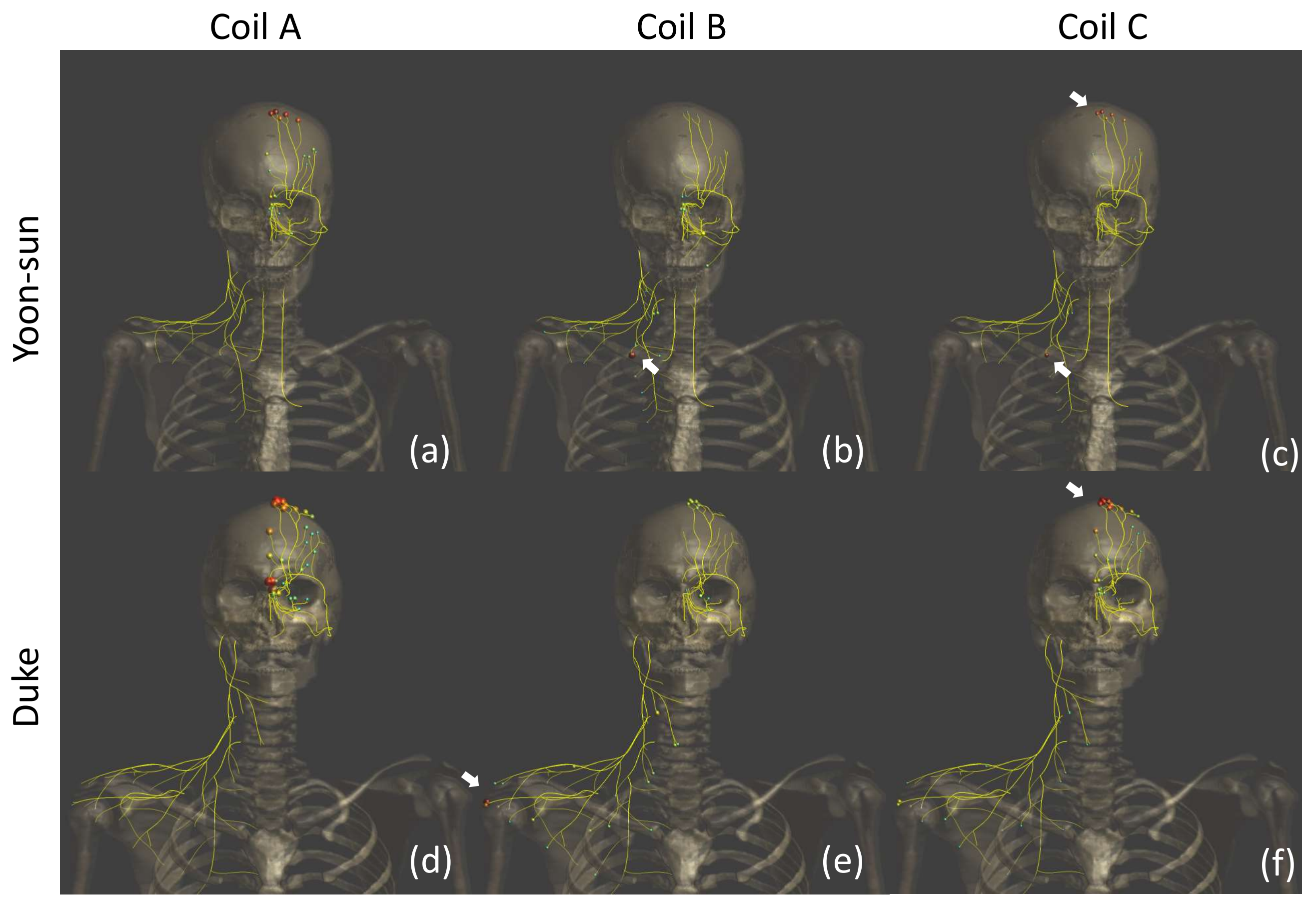
|E| field in Yoon-sun (scaled to 100mT/m/s)

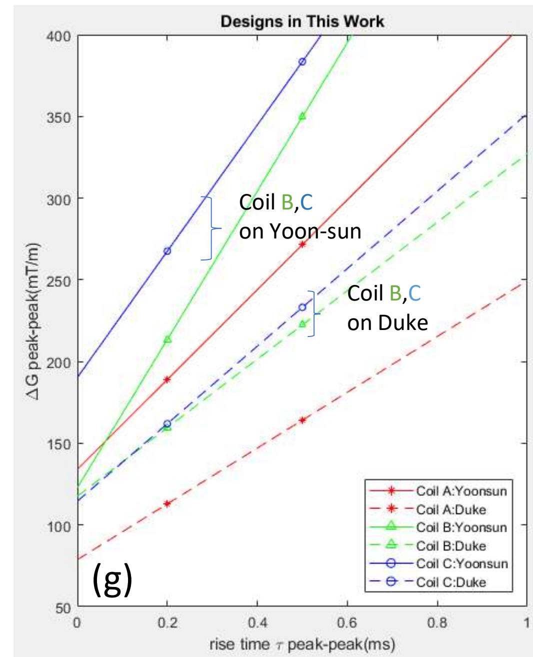
V/m

- For coil C, although |E| is higher in shoulder region than head(similar to Coil B), PNS result is opposite (see next page)

[1] Foo et al., Highly efficient head-only magnetic field insert gradient coil for achieving simultaneous high gradient amplitude and slew rate at 3.0T for brain microstructure imaging, MRM, 2020, 83: 2356–2369
[2] Davids et al. Peripheral nerve stimulation informed design of a high-performance asymmetric head gradient coil. *MRM,* 2023; 90: 784- 801.
[3] Roemer,et al. Minimum electric-field gradient coil design: Theoretical limits and practical guidelines. *MRM*. 2021; 86: 569– 580.

PNS Simulation Results

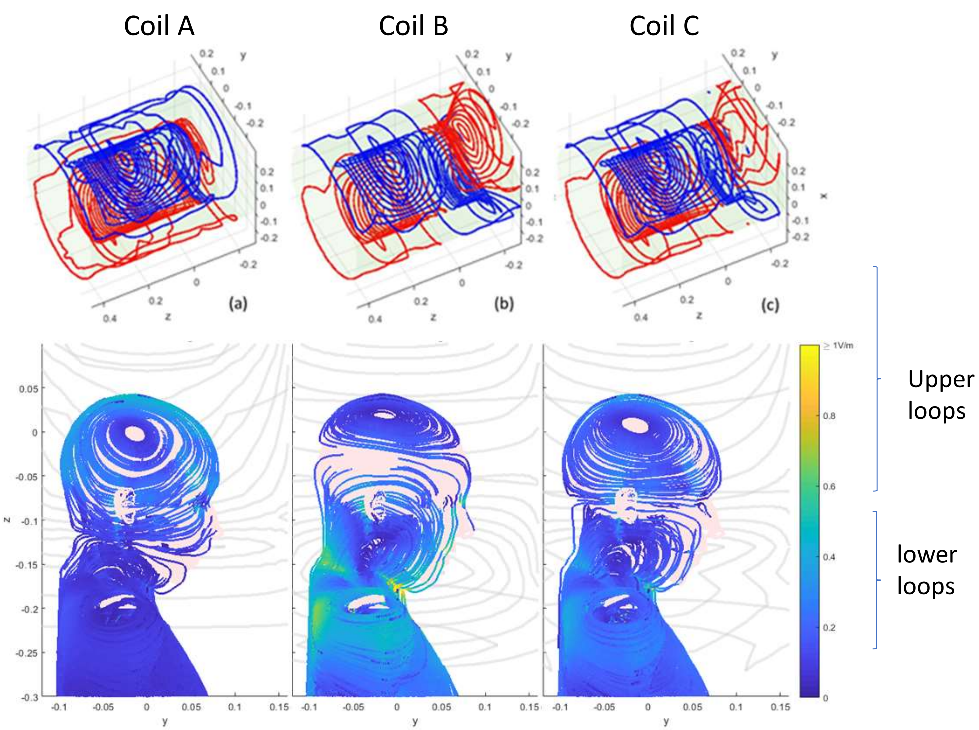




PNS Threshold for Coil A,B and C in Yoon-sun and Duke

- Coil B induced larger PNS at neck/shoulder region by having more turns nearby.
- Coil C has relative better balance for upper lower region of head
- PNS threshold is impacted by scan position

E-field Streamlines



$\vec{E}$ streamlines $(\vec{J} = \sigma\vec{E})$ scaled to 100T/m/s

- E-field streamline plot provides more intuition to understand the PNS sensitivity.
- To constrain the PNS is to change/balance the eddy current flow pattern in human body to avoid putting high e-field on nerves;

[1] Peter B. Roemer, Brian K. Rutt, Minimum electric-field gradient coil design: Theoretical limits and practical guidelines, MRM 86(1):569-580. 2021
[2] Hidalgo- Tobon SS, Bencsik M, Bowtell R. Reducing peripheral nerve stimulation due to gradient switching using an additional uniform field coil. MRM. 66:1498- 1509, 2011

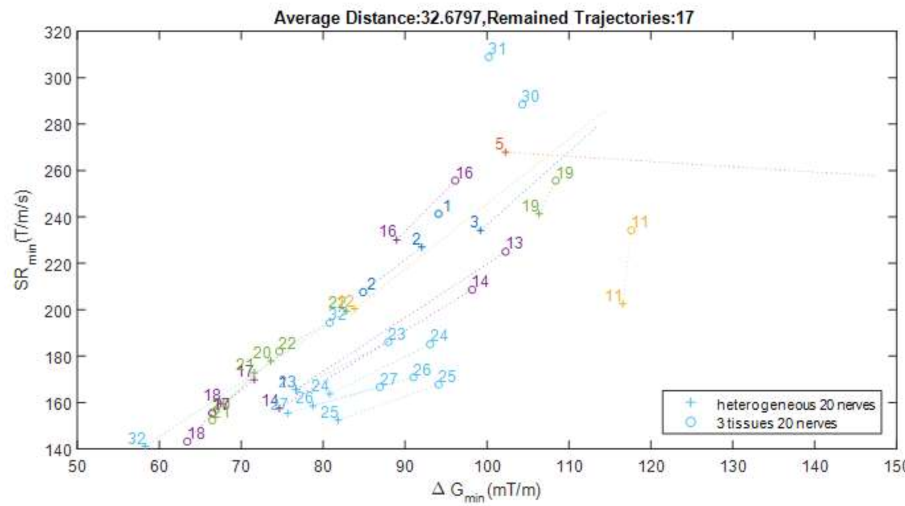
Impacts by Homogenous/Simplified Tissue Properties

- Homogenous model can enable BEM method to reduce the computation time[1]; IEC 60601-2-33: Simplified homogenous cylinder.
- Simplified human body model with several tissue properties instead of tens of different tissues can make the segmentation process easier[2] (Duke & Yoon-sun model has >70 tissues) → potential beneficial for personalized healthcare.

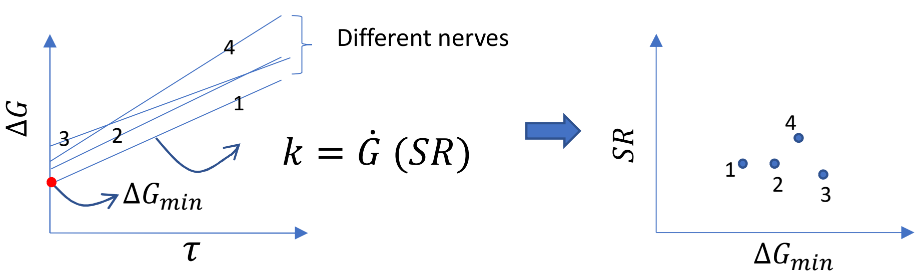
Investigate different tissue properties strategies:

- Heterogeneous(original tissue properties)
- Homogeneous (IEC 60601-2-33: 0.2[S/m])
- 3 tissues(fat, bone, muscle)
- 6 tissues(skin, fat, bone, lung, liver, muscle)

All other tissues



$$\Delta G(\tau, \vec{r}) = \Delta G_{min}(\vec{r}) + \dot{G}_r(\vec{r})\tau$$



	Tissue model	Avg. Dist.	Top Sensitive Nerve #(of 20)
MAGNUS X	6 tissues	16.6	19
	3 tissues	32.7	17
	homogeneous	48.6	16
MAGNUS Z	6 tissues	5.9	19
	3 tissues	57.1	8
	Homogeneous	110.4	8

[1] Peter B. Roemer, Brian K. Rutt, Minimum electric-field gradient coil design: Theoretical limits and practical guidelines, MRM 86(1):569-580. 2021
[2] Fujimoto K, et al. Simplifying the Numerical Human Model with k-means Clustering Method. 2020 Aug 6. In: Makarov SN, Noetscher GM, Nummenmaa A, editors. Brain and Human Body Modeling 2020: Computational Human Models Presented at EMBC 2019 and the BRAIN Initiative® 2019 Meeting

Conclusions

- Better agreement is achieved between simulation and measurement for PNS test by adding extracranial and superficial nerve trajectories in the head and upper body; Gradient coil design needs a relative complete nerve atlas for scanning places of interest.
- The essence of changing PNS threshold by changing the gradient coil wire pattern is that through changing or balancing the eddy current flow pattern in human body, to avoid putting high e-field on nerves.

Acknowledges

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Thank you for your attention

yihe.hua@ge.com