Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Are We There Already or Can We Do Better?

– A Slightly Different Angle on Safe Implant Scanning

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Declaration of ~~Financial~~ Interests or Relationships

Speaker Name: Bernd Ittermann

Caution: some serious advertising ahead

Alternative title:

If our implant (lead/electrode) had a sensor …

… and our scanner a parallel transmit (pTx) system,

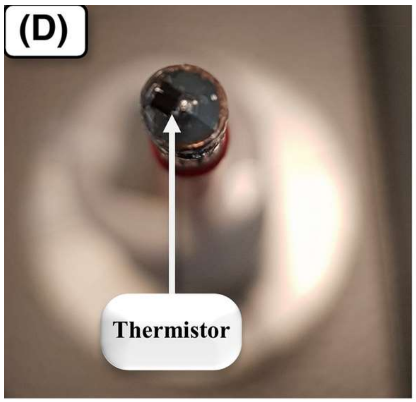
what could that be good for ?

Outline

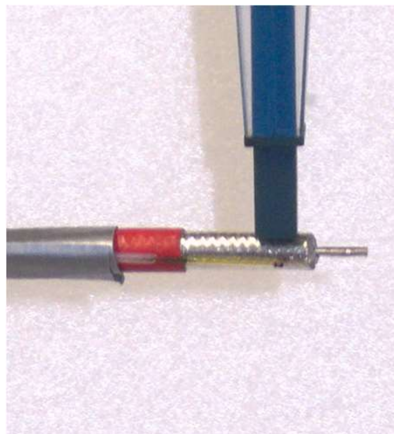
- Implant sensors and how to utilize them
- pTx: combining image quality and safety
- Some aspects of a practical implementation
- Conclusion

Are implant sensor doable?

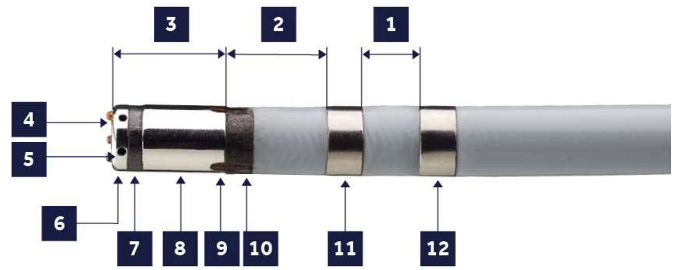
- yes



B. Silemek et al., MRM 2022



J. Petzold et al., ISMRM 2023
“remote” implant sensor



global.Medtronic.com: ablation catheter tip with 6 thermocouples

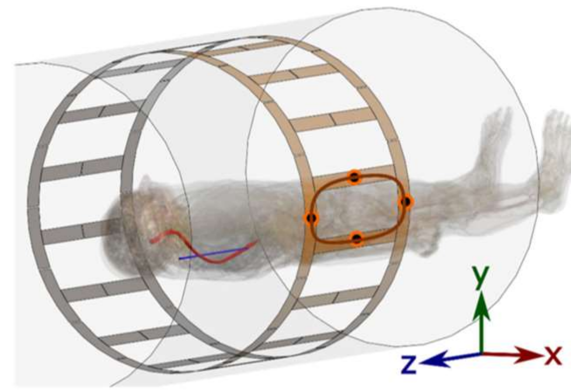
- ok, they may be doable, but are they worth it?

Simulation setup

The model

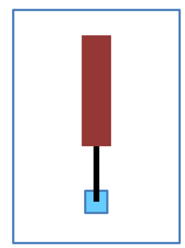
- Generic 8-ch body coil at 3 T
- ‘Duke’, dummy implant touching spinal cord, heart at $z = 0$

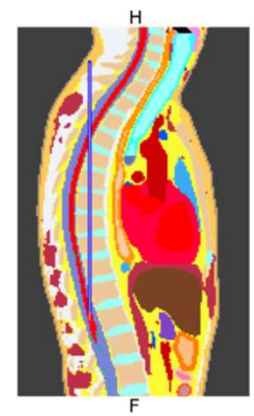
  Sim4Life 5.0, 2 mm iso, 48 ports, co-simulations, Pennes, VOP’s



The “sensors”

- Computed physical quantities at or around implant tip
  - SAR, $|E_z|^2$, $|B_1|^2$, dT/dt averaged over (4 mm)^3 around tip
  - I_{RF} at $d_1 = 10\ \mathrm{mm}$ or $d_2 = 250\ \mathrm{mm}$ from tip





The hazard metrics

- $\mathrm{SAR_{pt}}$, $\mathrm{SAR_{10g}}$, T_{SS}, ΔT_{imp}

Data processing: the native case

Calculation of point Q-matrices:

excitation voltage vector

$$\text{SAR}(\boldsymbol{r},\boldsymbol{u}) = \frac{\sigma(\boldsymbol{r})}{2\varrho(\boldsymbol{r})}|\boldsymbol{E}(\boldsymbol{r},\boldsymbol{u})|^2 = \boldsymbol{u}^\dagger \boldsymbol{Q}_{\mathrm{pt}}(\boldsymbol{r})\boldsymbol{u}$$

Averaging to get 10g Q-matrices + head + whole body + partial body:

$$\boldsymbol{Q}_{\mathrm{pt}}(\boldsymbol{r}) \to \boldsymbol{Q}_{\mathrm{A}}^{(k)}$$

Normalization to IEC limits L:

$$\widehat{\boldsymbol{Q}}_{\mathrm{A}}^{(k)} = \frac{\boldsymbol{Q}_{\mathrm{A}}^{(k)}}{L^{(k)}}$$

VOP calculation:

$$\widehat{\boldsymbol{Q}}_{\mathrm{A}}^{(k)} \to \widehat{\boldsymbol{Q}}^{(k)}$$

$$\max_k \, u^\dagger \widehat{Q}^{(k)} u \quad \begin{cases} \leq 1 & \stackrel{\text{def}}{=} \quad u \text{ is safe} \\ > 1 & \stackrel{\text{def}}{=} \quad u \text{ is unsafe} \end{cases}$$

Q_S – the sensor Q matrix

$\text{SAR}(\boldsymbol{u}) = \boldsymbol{u}^{\dagger}\boldsymbol{Q}_{\text{SAR}}\boldsymbol{u}$ ↔ Sensor signal $X(\boldsymbol{u}) = \boldsymbol{u}^{\dagger}\boldsymbol{Q}_{\text{S}}\boldsymbol{u}$

$$Q_{S,kl}^{X} = \begin{cases} (X_{kl} - X_k - X_l) + j\left(X_{kl}^{\dagger} - X_k - X_l\right) & \text{for } k \neq l \text{ and } k < l \\ (X_{kl} - X_k - X_l) - j\left(X_{kl}^{\dagger} - X_k - X_l\right) & \text{for } k \neq l \text{ and } k > l \\ 2X_k & \text{for } k = l \end{cases}$$

X_k: sensor signal if only channel k transmits
X_{kl}: sensor signal if channels k and l transmit in phase
$X_{kl}^{\dagger}$: sensor signal if channels k and l transmit 90° out of phase

N channels → N^2 measurements → $\boldsymbol{Q}_{\text{S}}$ determines sensor response to all possible excitations

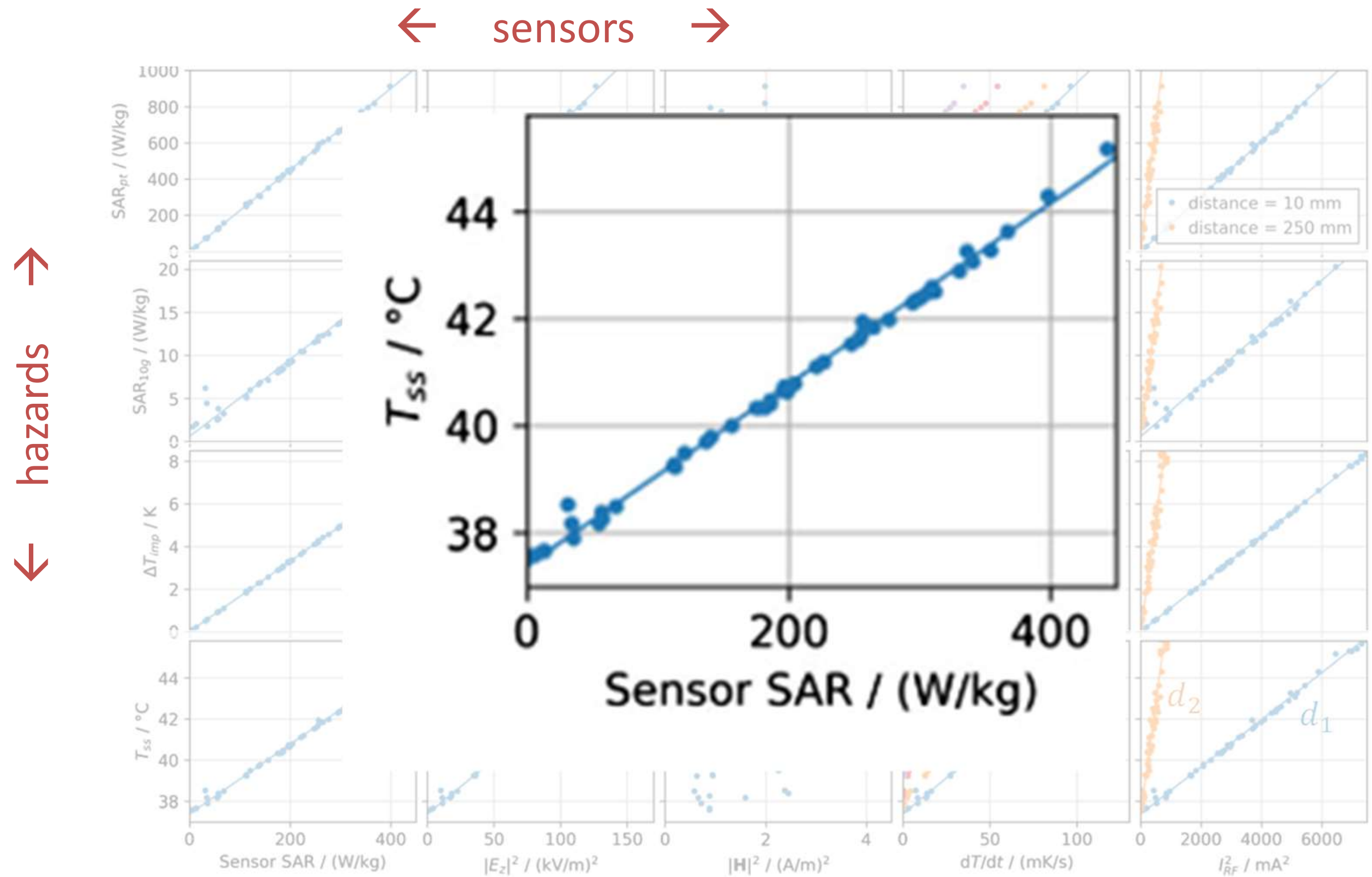
Normalization: $\widehat{\boldsymbol{Q}}_{\boldsymbol{s}} = \boldsymbol{Q}_{\boldsymbol{s}}/q_{\text{lim}}$

q_{lim} = max. permissible sensor reading, to be defined

B Silemek et al., MRM 2022
L Alon et al, MRM 2013; N Boulant et al., MRM 2016

Sensor calibration

- 100 random excitations → calculate sensor signals and hazard measure



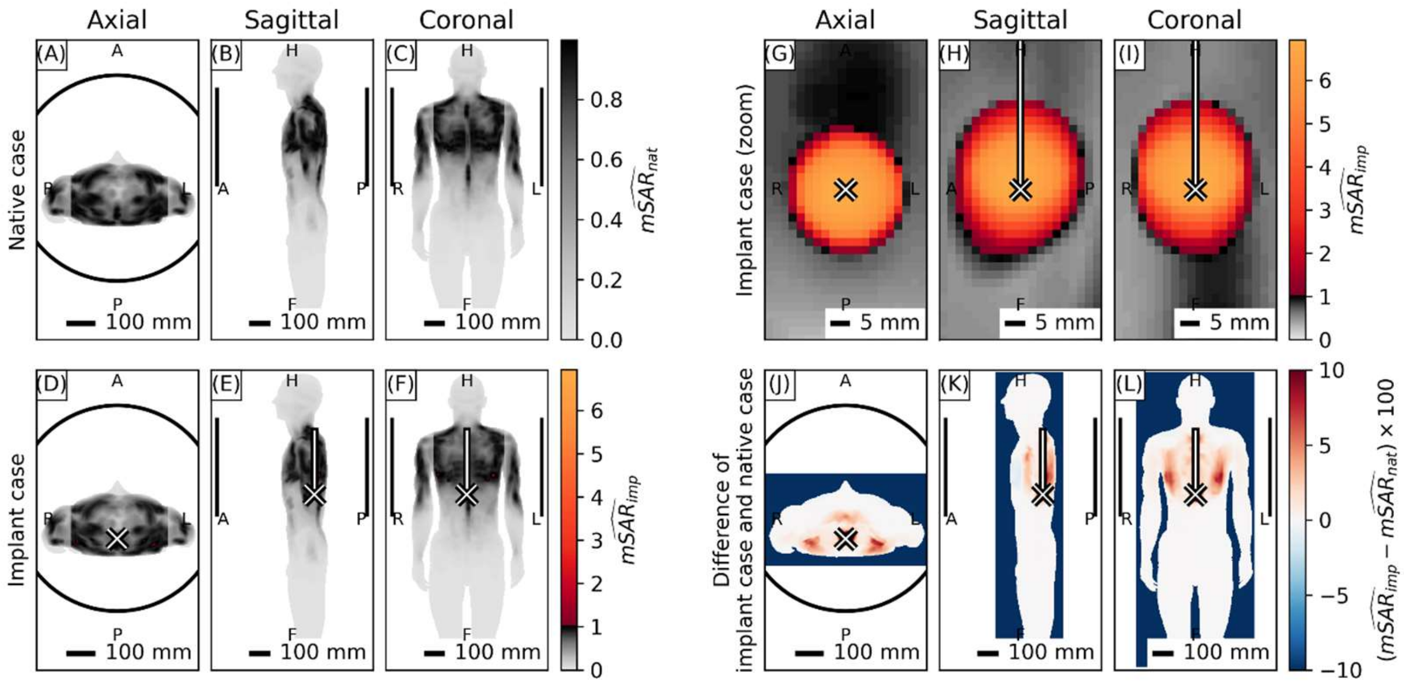
Native safety vs implant safety

Same excitation vector with or without implant ($\hat{Q}_s$ ignored)

- normalized SAR MIPs → single hotspot at implant tip + minor global effects

native

implant

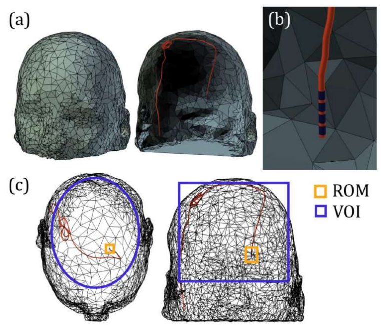


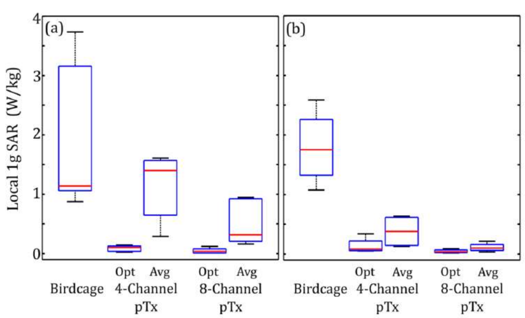
implant zoom

implant - native (magnified)

Step 2: pTx

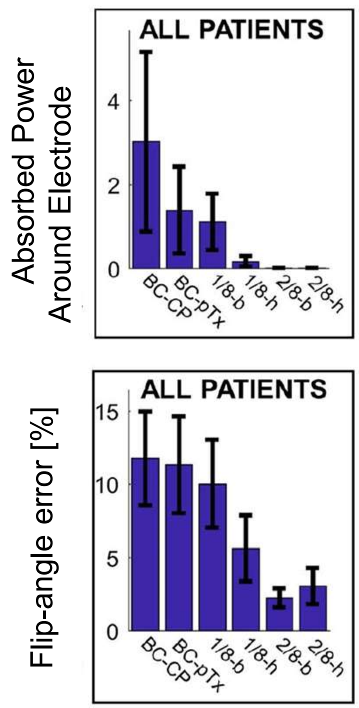
- pTx is only good for 7T, right?
- Well, not really





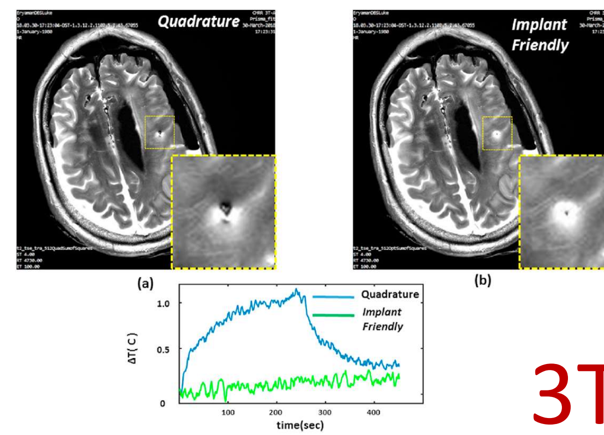
McElcheran CE et al., MRM 2017
McElcheran CE et al., Sci Rep 2019

3T



3T

Guerin B et al., MRM 2020



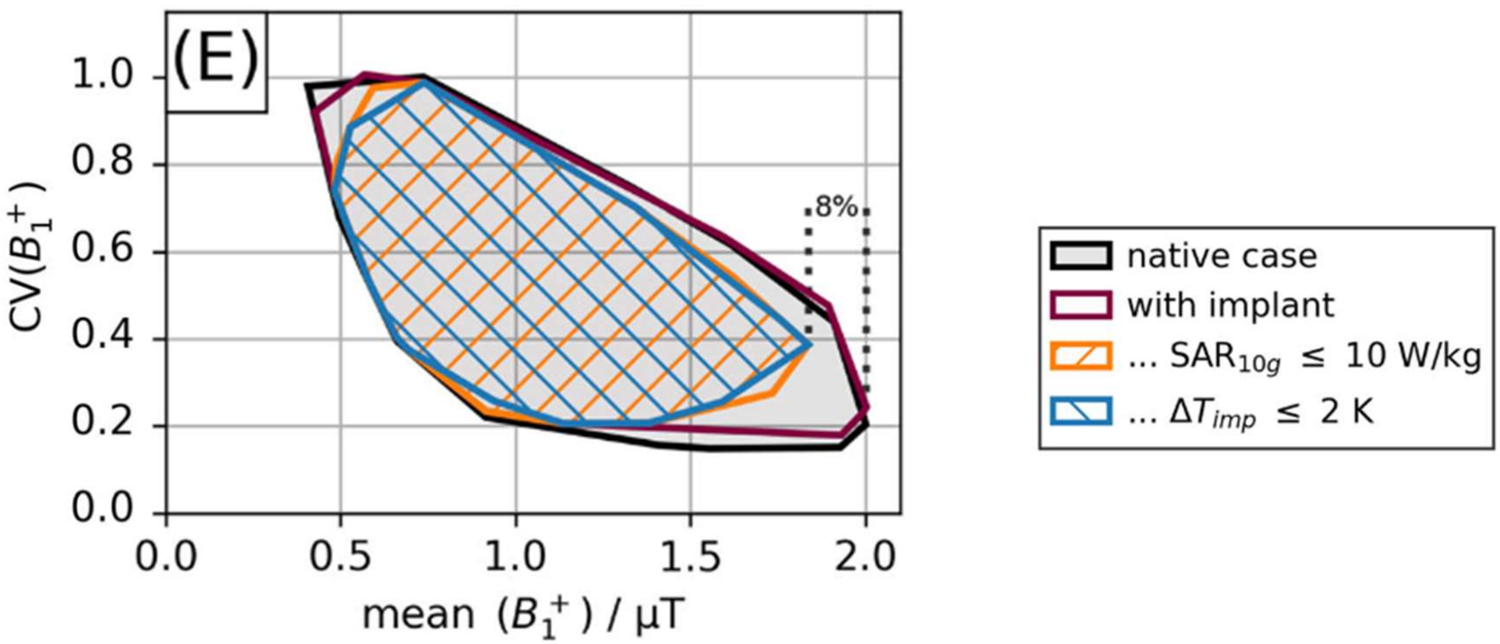
3T

Eryaman Y et al., *NeuroImage* 2019

pTx and image quality

- Simplest possible pTx application: static RF shimming
- Quality metric: $\mathrm{mean}(B_+^1)$, $\mathrm{CV}(B_+^1)$

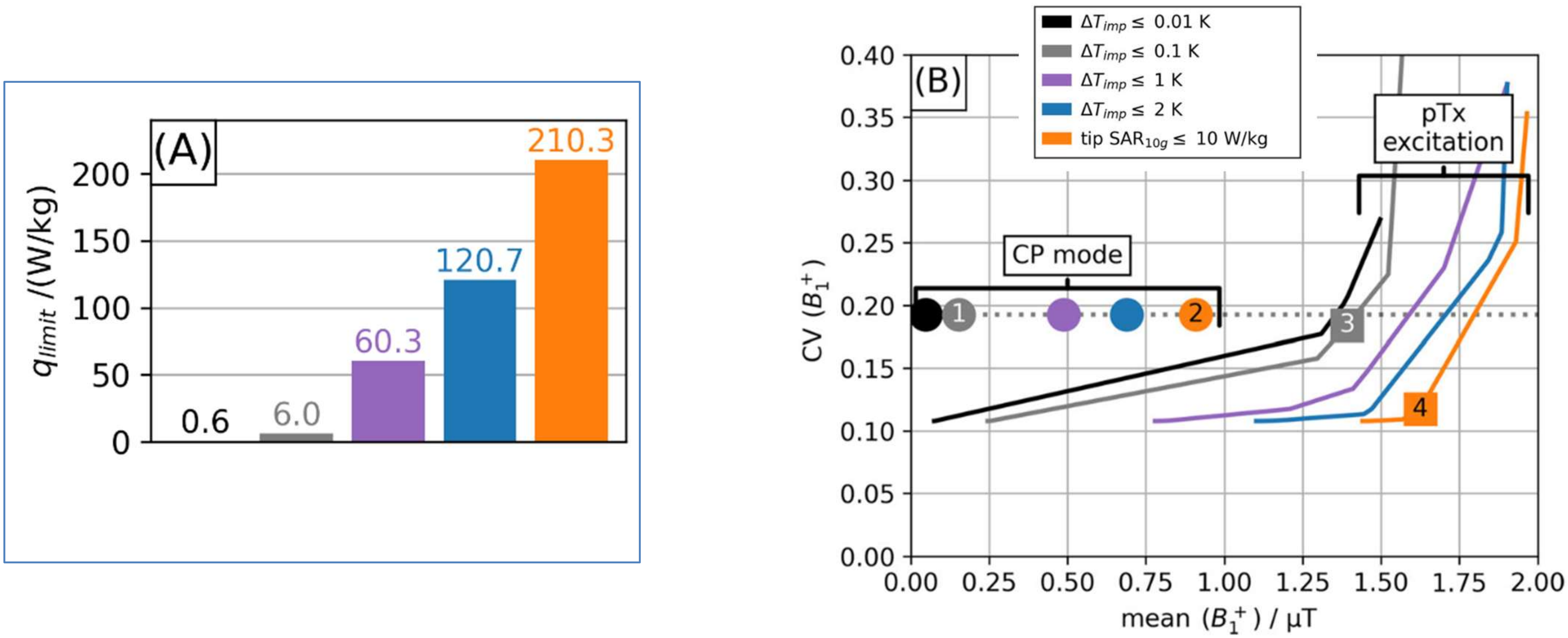
20 000 random excitations



J Petzold et al., NMR Biomed 2023

Optimizing image quality

- trade-off between high $\mathrm{mean}(B_{+}^{1})$ and low $\mathrm{CV}(B_{+}^{1})$
- image quality is the target, safety the constraint



J Petzold et al., NMR Biomed 2023

B_+^1 maps

- trade-off between high $\text{mean}(B_+^1)$ and low $\text{CV}(B_+^1)$

CP

$\text{SAR}_{10g} \leq 10$ W/kg

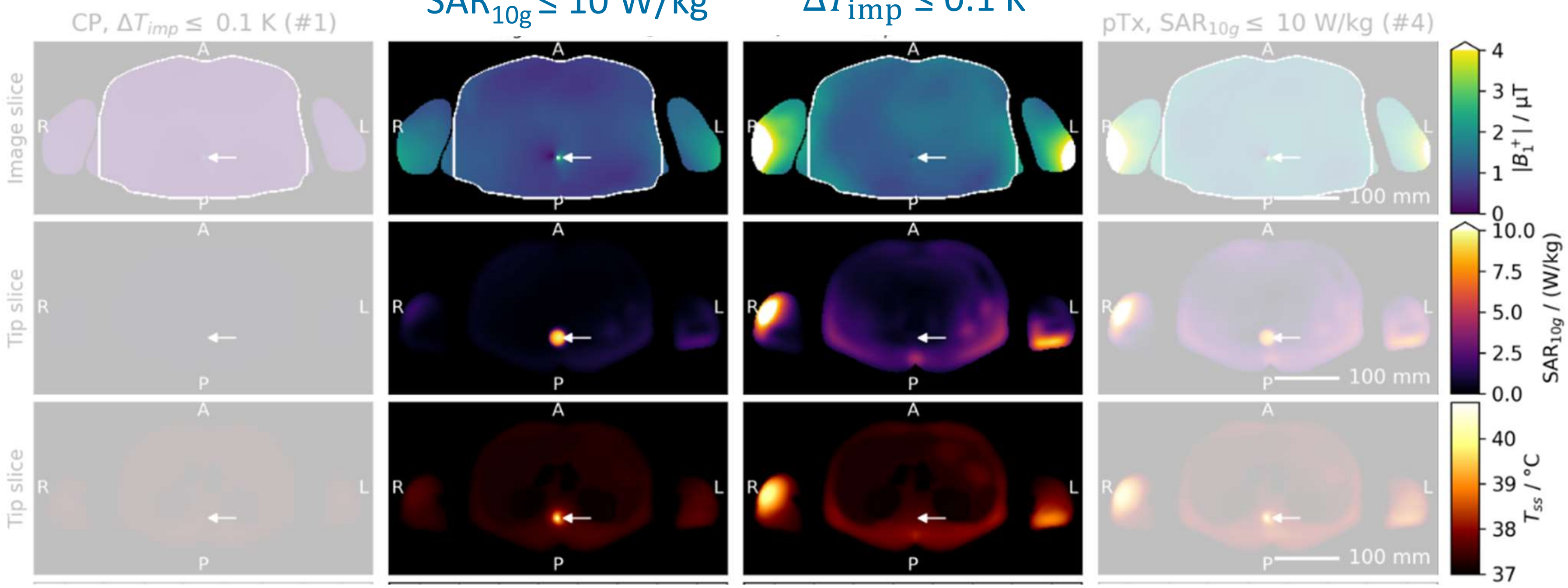
pTx

$\Delta T_{imp} \leq 0.1$ K

B_+^1
image slice

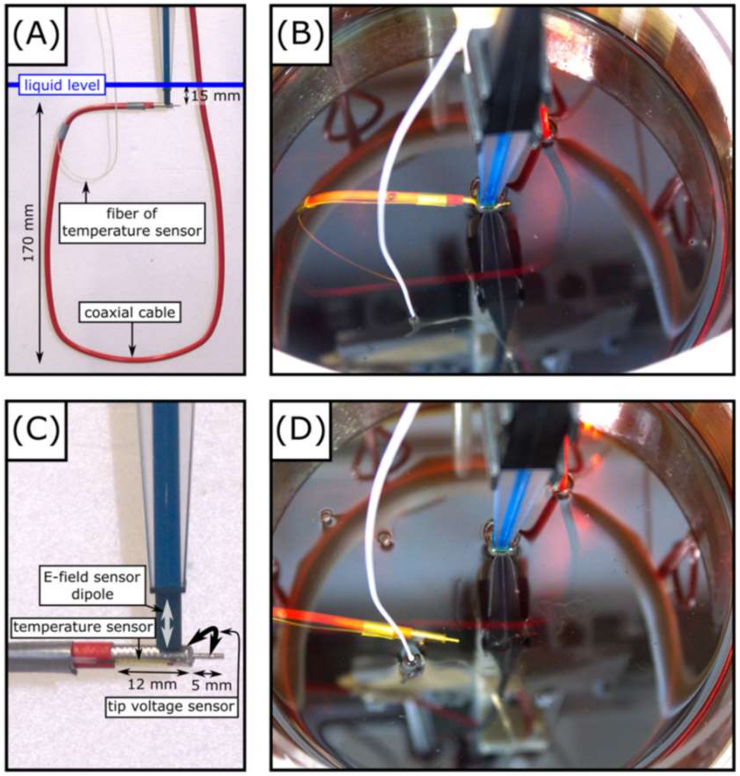
SAR_{10g}
tip slice

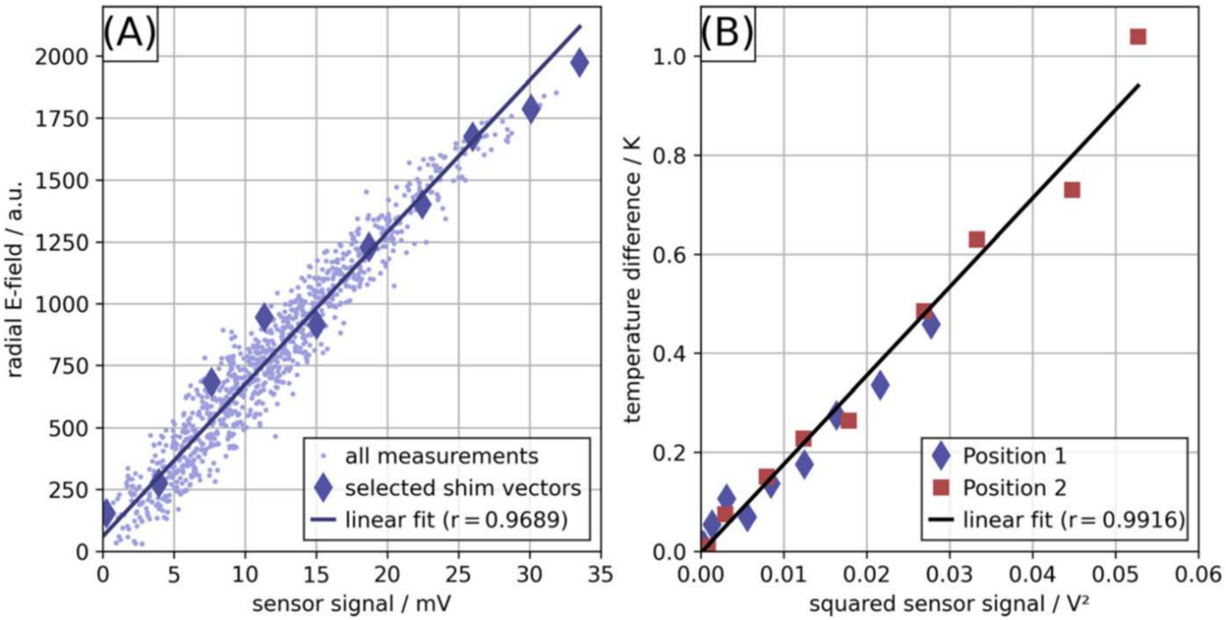
T_{ss}
tip slice



Simulate and validate

- experimental calibration of the implant sensors against external probes

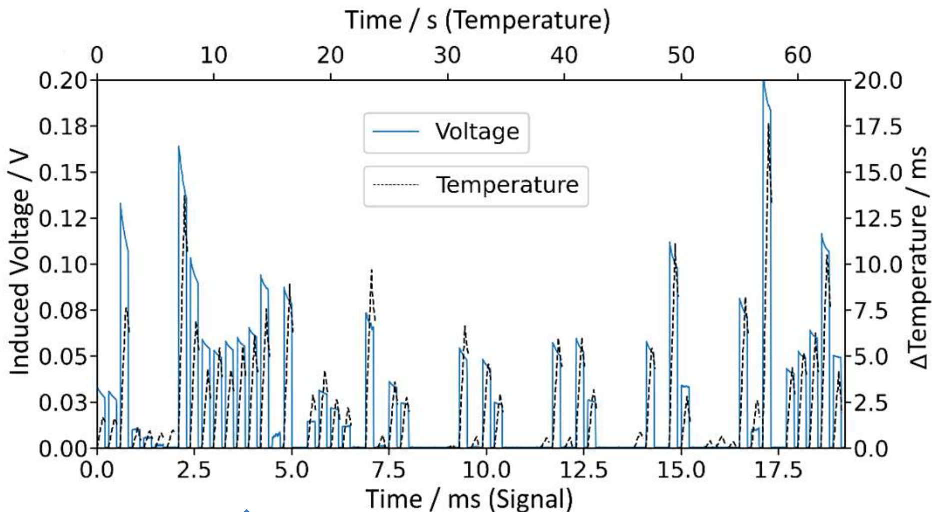




J Petzold et al., ISMRM 2023

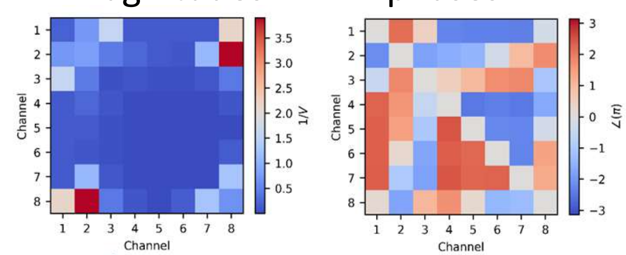
Measuring Q_s

- Measurements for a T or E-field sensor



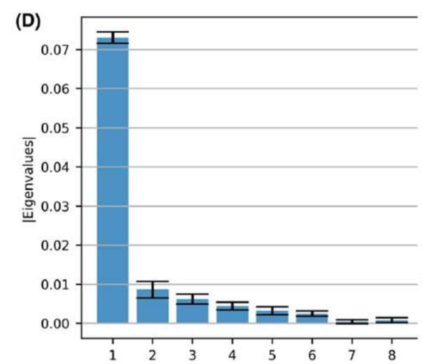
1

Q_S^E



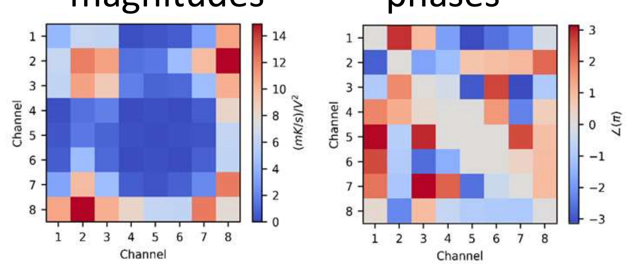
2

Q_s Eigenvalues



1

Q_S^T



2

Q_S vs the state of the art?

- ISO 10 974, Tier 3: the Transfer Function (TF)

From: SM Park, R Kamondetdacha, JA Nyenhuis, JMRI 2007

$$E_s(P) \approx E_1(P) \int_0^L S_1(s) E_{\tan}(s)\, ds \qquad (2)$$

$$\alpha \equiv \int_0^L S_1 E_{\tan}\, ds \qquad (3)$$

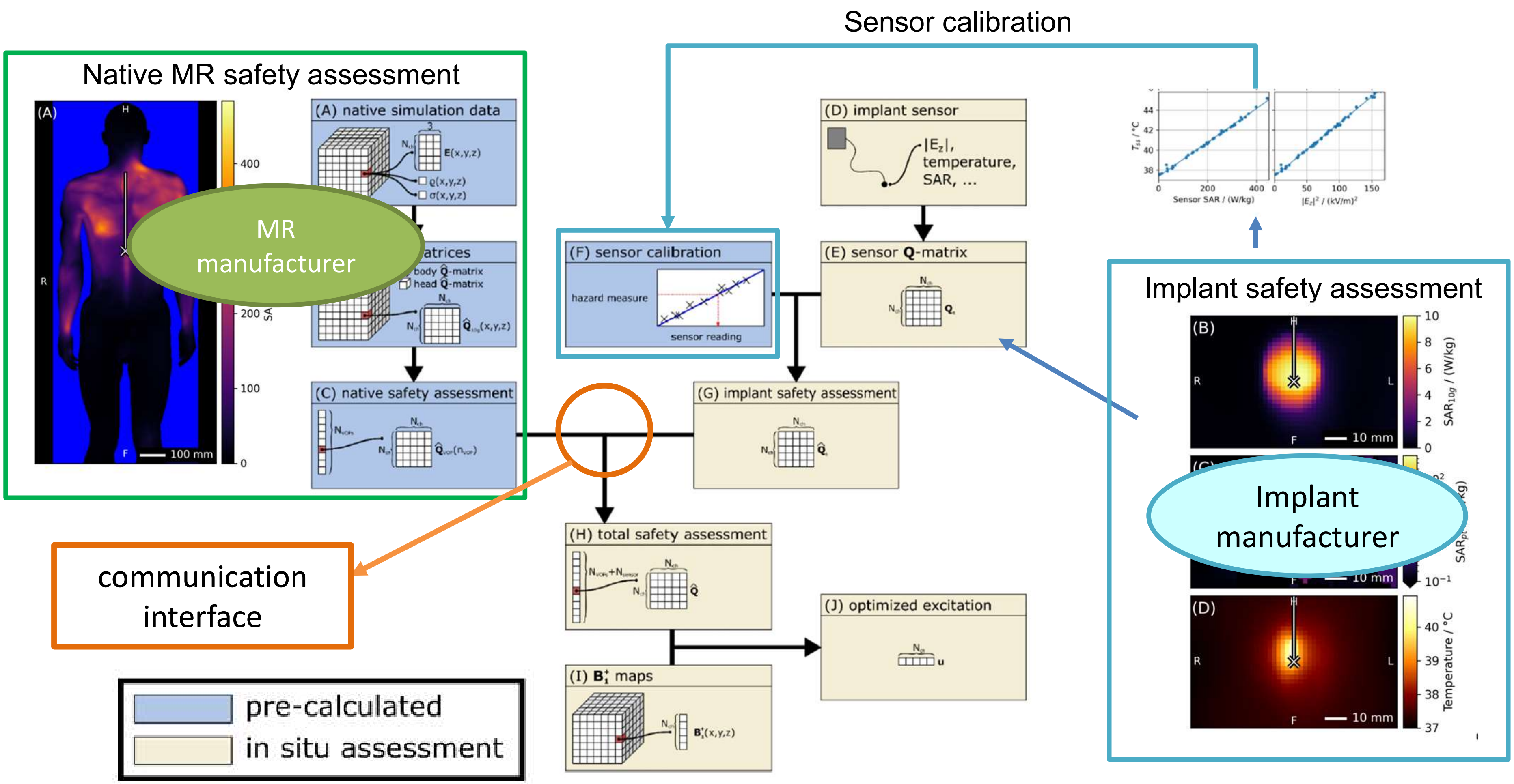
$$\mathrm{SAR}(\boldsymbol{u}) = \boldsymbol{u}^\dagger |\alpha|^2 \boldsymbol{u} \qquad (4)$$

Reminder:

Sensor signal: $X(\boldsymbol{u}) = \boldsymbol{u}^\dagger \boldsymbol{Q}_S \boldsymbol{u}$

- $\boldsymbol{Q}_S$ is the Transfer Function integral
  - for the actual patient in the scanner
  - evaluated along the actual implant trajectory
  - and the actual E-fields in the body

An 'integrated safety concept'



Summary

- Sensor based implant safety concept
- Restrictions
- In situ asses
  - patient's
  - implant tr
  - MR scann

But if scanner and implant set the scan conditions by themselves, are we still responsible then?

Sorry guys, but no: you're out!

- Ultimate goal
  - Scanner and implant communicate directly, negotiate RF settings

Acknowledgements

ISMRM Safety SG award 2023
3rd prize

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ISMRM Safety SG award 2023
1st prize

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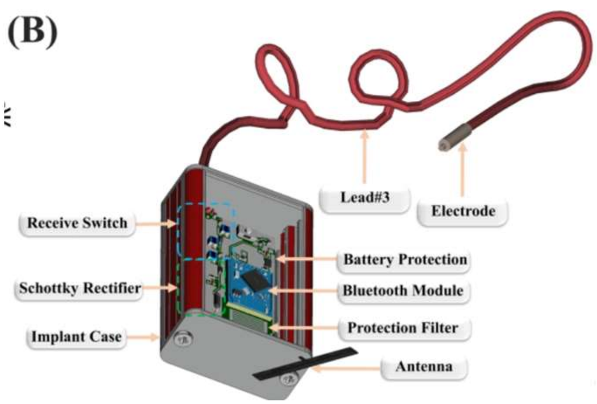
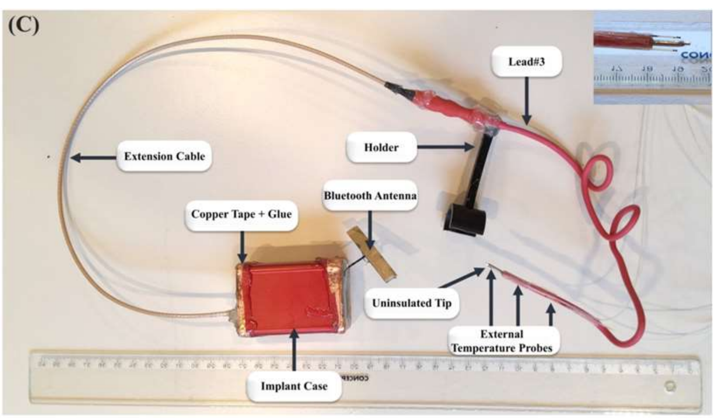
How to get the signal out?

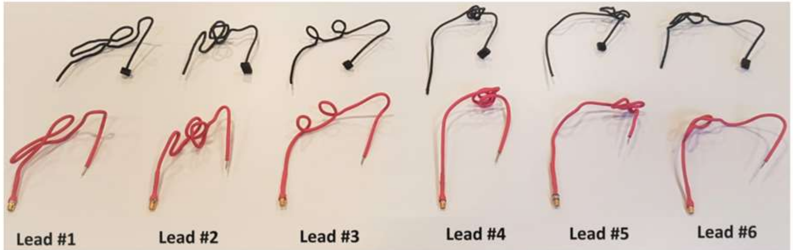
- Sensor embedded wireless reference implant



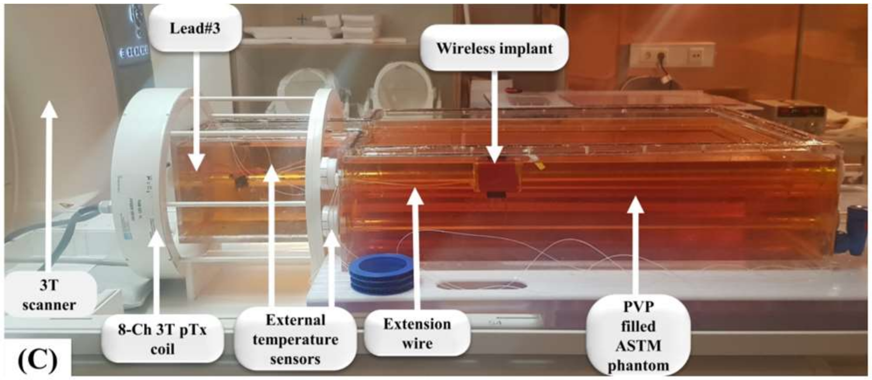


Realistic DBS lead trajectories

(B Guerin et al, Phys Med Biol 2019)



3T experimental setup



B Silemek et al., MRM (under review)

Sensor calibration

- 100 random excitations → calculate sensor signals and hazard measure