Interdisciplinary Science: Small-scale coils for Transcranial Magnetic Stimulation

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Transcranial Magnetic Stimulation

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Is this physics?

Yes. But it is also:
Biology, Medicine,
Computer Science,
Engineering…

Co-authors (this presentation)
Jake Waas (computer science)
Alex Tang (animal physiology)
Kartik Iyer (electronic engineering)
Jenny Rodger (anatomy, genetics)

Some other Collaborators
John Reynolds (electrophysiology)
John Shemmell (TMS)
Nigel Rogasch (Medical imaging, TMS)
Ben Fulcher (physics)
Peter Robinson (physics)

Outline

- The physics
- Some challenges
- Making small-scale coils for mice
  - Scaling problems
  - Can we create large fields?
  - What can be modelled?
  - Problems of interpretation
- Conclusions

No fantastic results yet – just problems

The Physics

- Electromagnetic Induction

$\vec{A}_0$ depends on coil

$\vec{A}_1$ depends on induced currents

- $\vec{A} = \frac{\mu N}{\pi} I \left(\frac{r}{mx}\right)^{1/2} [K(m)(1 - m/2) - E(m)]\hat{\vec{\varphi}} + \vec{A}_1$

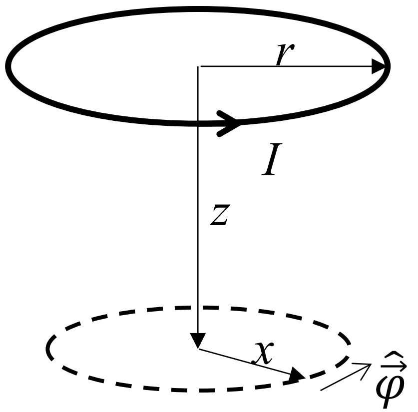
where $m = \frac{4rx}{(r+x)^2+z^2}$ and K and E are elliptic functions

- $\vec{B} = \vec{\nabla} \times (\vec{A}_0 + \vec{A}_1)$
- $\vec{E} = -\frac{\partial \vec{A}_0}{\partial t} - \frac{\partial \vec{A}_1}{\partial t} - \vec{\nabla} u$

Depends on inhomogeneity in tissue conductivity (and coil & positioning). **Hard**

Depends only on coil and positioning. **Easy**

Zero if dI/dt = constant since induced currents and therefore A_1 constant



Some fundamental challenges

- We know how EM Induction works
- We don't know more-or-less everything else about TMS*
  - TMS practice over the last three decades has not generally been based on scientific understanding
  - We don't have a good idea of how the induced fields interact with the brain to produce observable changes
  - Limited work on animals
  - Limited modelling work
- **Can we put TMS back in the realm of science?**

*Maybe a bit of an exaggeration for dramatic effect

Experiments with small animals

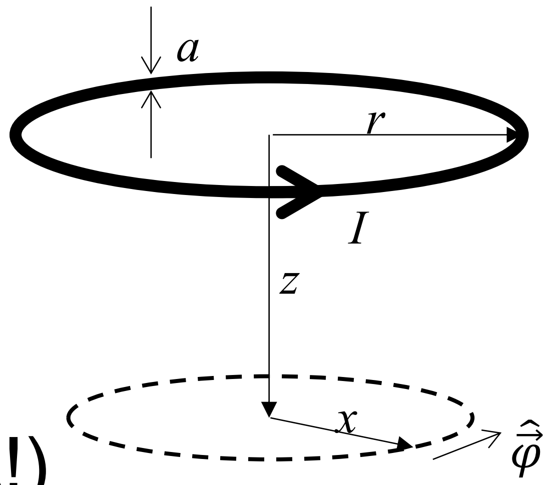
- Apply TMS to mice
- Measure outcomes more directly than for humans
- But:

Need coils built for mice

Rodger & Sherrard. (2015). Neural Regeneration Research, 10(3), 357-359

The problem with small

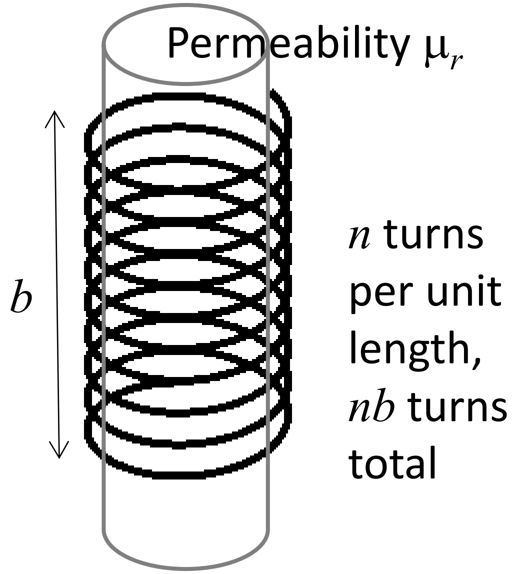
- Use dimensional analysis (look at units in terms of length, mass, time, current)
- $\boldsymbol{B} = \frac{\mu\, I}{r} \boldsymbol{f}\left(\frac{x}{r}, \frac{z}{r}\right) = \frac{\mu\, I}{r} \boldsymbol{f}(geometry)$
- $\boldsymbol{E} = \mu \frac{dI}{dt} \boldsymbol{g}\left(\frac{x}{r}, \frac{z}{r}\right) = \mu \frac{dI}{dt} \boldsymbol{g}(geometry)$
- Do we talk about E or B? They behave differently
- To get same E-field we need same current (=6000 A!)
- $Q = \frac{N\rho\, I^2}{r}\, h\left(\frac{a}{r}\right)$
- Heat per unit area scales as $1/r^3$

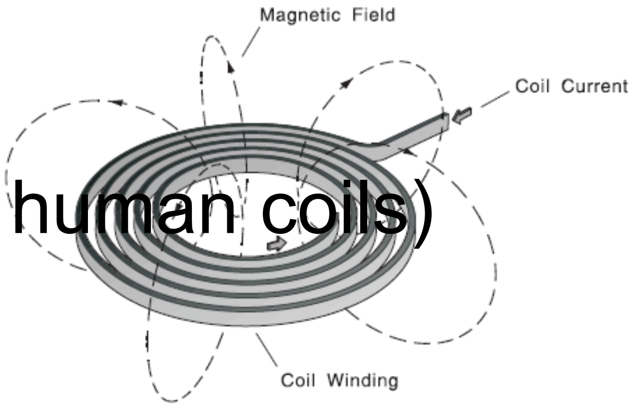


The paradox of inductance

$$\Phi = L\,I, \qquad V = L\,\frac{dI}{dt}$$

- EM Induction
- We want a large, rapidly changing magnetic field
- But:
  - Larger B-fields imply larger inductance
  - Larger inductances implies slower changes
- Two competing effects – which wins out?
  - Long coils or short coils?
  - High turn density or low turn density
  - High permeability or low permeability core?
- Short coils, few turns are favourable (commercial human coils)

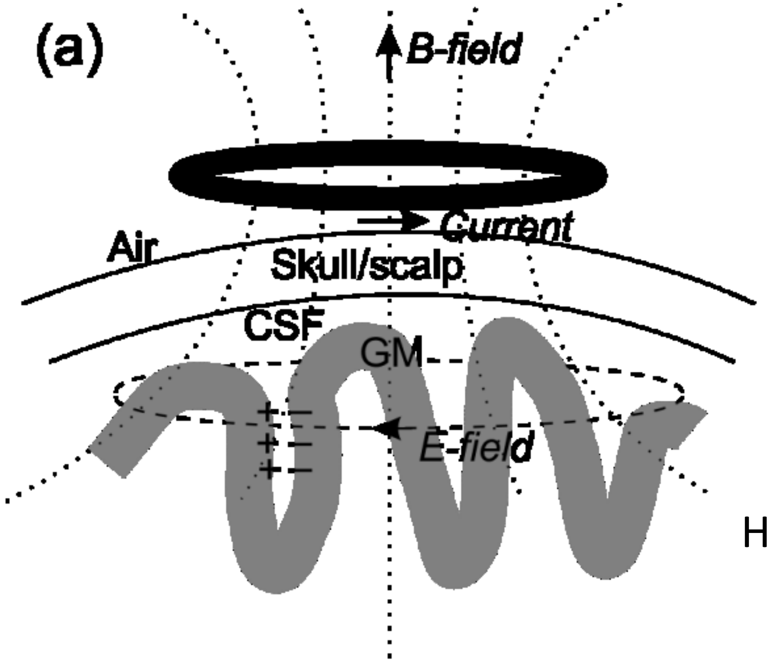




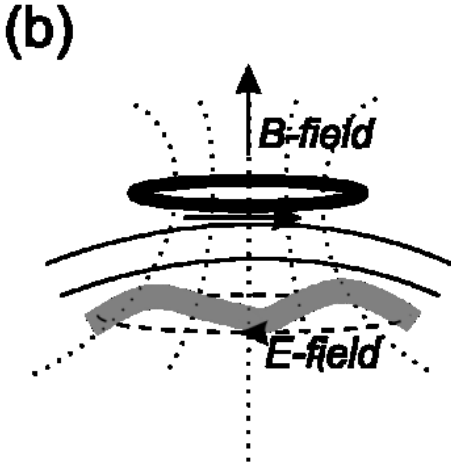
How do we model the effect on the brain?

- SimNIBS www.simnibs.de
  - Finite Element Model of human head stimulated with TMS coil
  - Can read in MRI data
  - Allows calculation of electric fields at surface of cortex
- No equivalent for mouse
  - simNIBS and the software it depends on (e.g. Freesurfer) makes assumptions about the nature of data
  - Assumed to be human data
- Not trivial to get around this but we think it possible

But mice aren't miniature humans anyway



Human



Mouse

- Human brain much more folded
  - Much greater charge separation and E-field distortion
- Can we compare fields between the two cases?
  - Is the mouse case meaningful?

Conclusions

- Making good small-scale coils is a challenge
- Interpreting results isn't straightforward
- A great lesson in applied electromagnetism
- Need:
  - Physicists
  - Engineers
  - Animal biologists
  - Computer Scientists
  - Medical professionals
  - Etc.