Thermal Analysis of Magnetically-Guided Cochlear Implant Surgery in a Model of the Cochlea

Fateme Esmailie, Professor Mathieu Francoeur, Professor Tim A. Ameel

Department of Mechanical Engineering
University of Utah
Presenter: Fateme Esmailie
fateme.esmailie@utah.edu

COMSOL CONFERENCE
2018 BOSTON

Overview

COMSOL CONFERENCE 2018 BOSTON

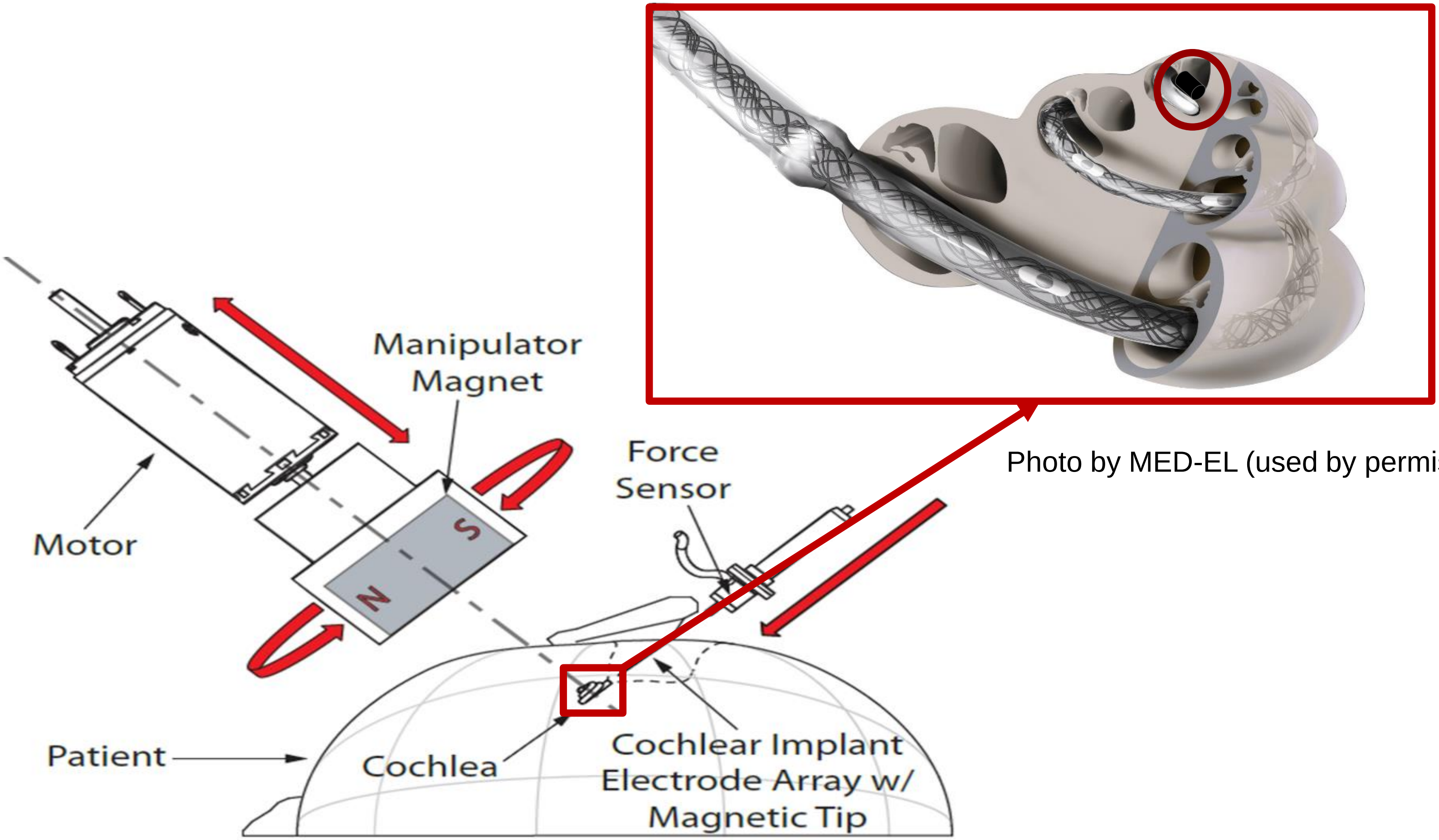
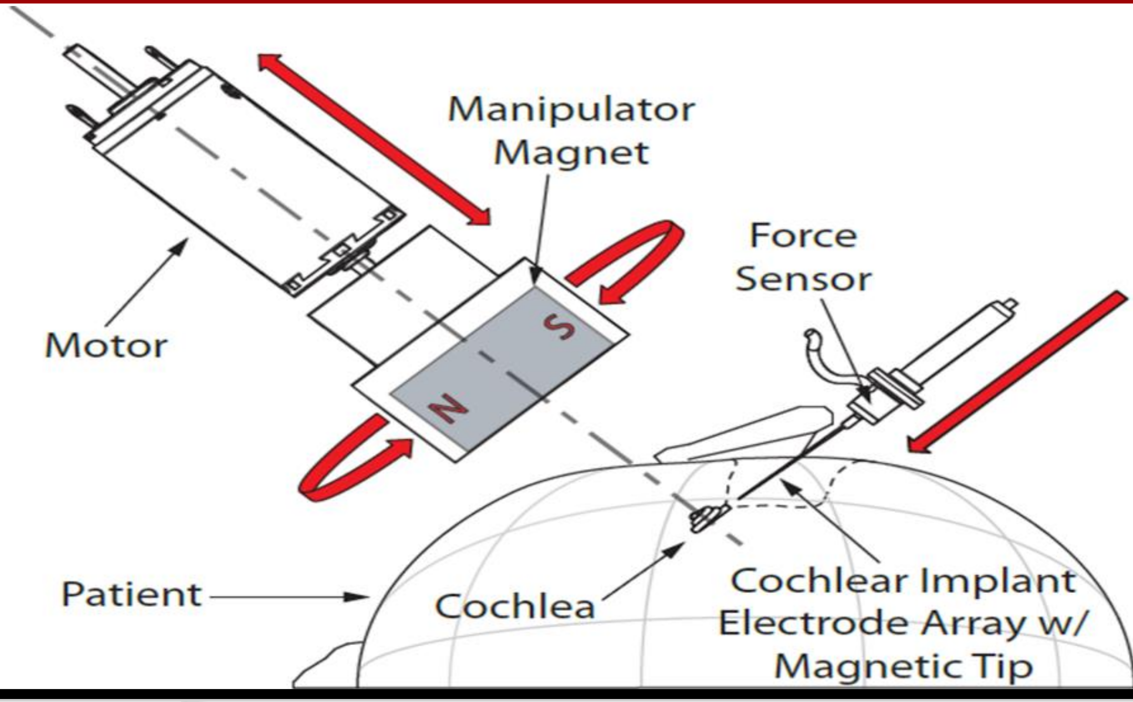


Photo by MED-EL (used by permission)

Clark et al., *Journal of Medical Devices*, 2012

Magnetic guidance of cochlear implant – surgical setup



Why magnetic guidance is required?

Clark et al., *Journal of Medical Devices*, 2012

Motivation of magnetic guidance of cochlear implant

450,000 people cochlear implant users worldwide

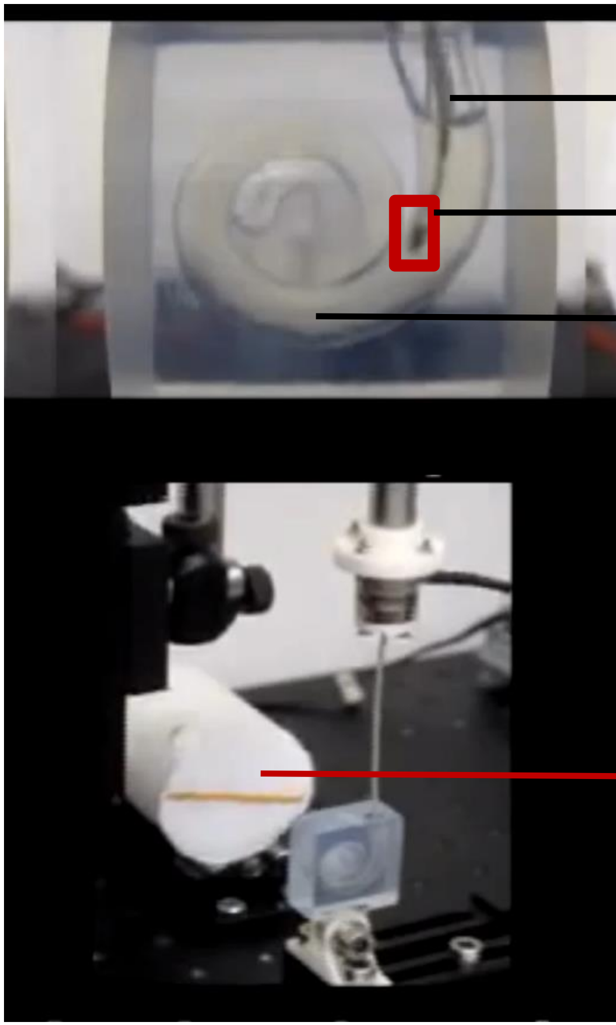
(http://www.cochlear.com/au/home/connect/cochlear-hearing-ambassador, 09/19/2019)

Manual insertion

Risk:
Intra-cochlear physical trauma
(33% of insertions)
(Finley et al., 2008)

One proposed solution : **Magnetic guidance**

Background – magnetic guidance



Cochlear implant electrode array

Magnet attached to the tip of cochlear implant electrode array

Chochlea phantom

Magnet that guides the cochlear implant electrode array

https://www.telerobotics.utah.edu/

Thermal challenges of magnetic insertion of a cochlear implant

Photo by MED-EL (used by permission)

To avoid medical complications

↓

Magnet detachment and removal

↓

Risk: thermal trauma

Requires

Thermal analysis of magnet detachment

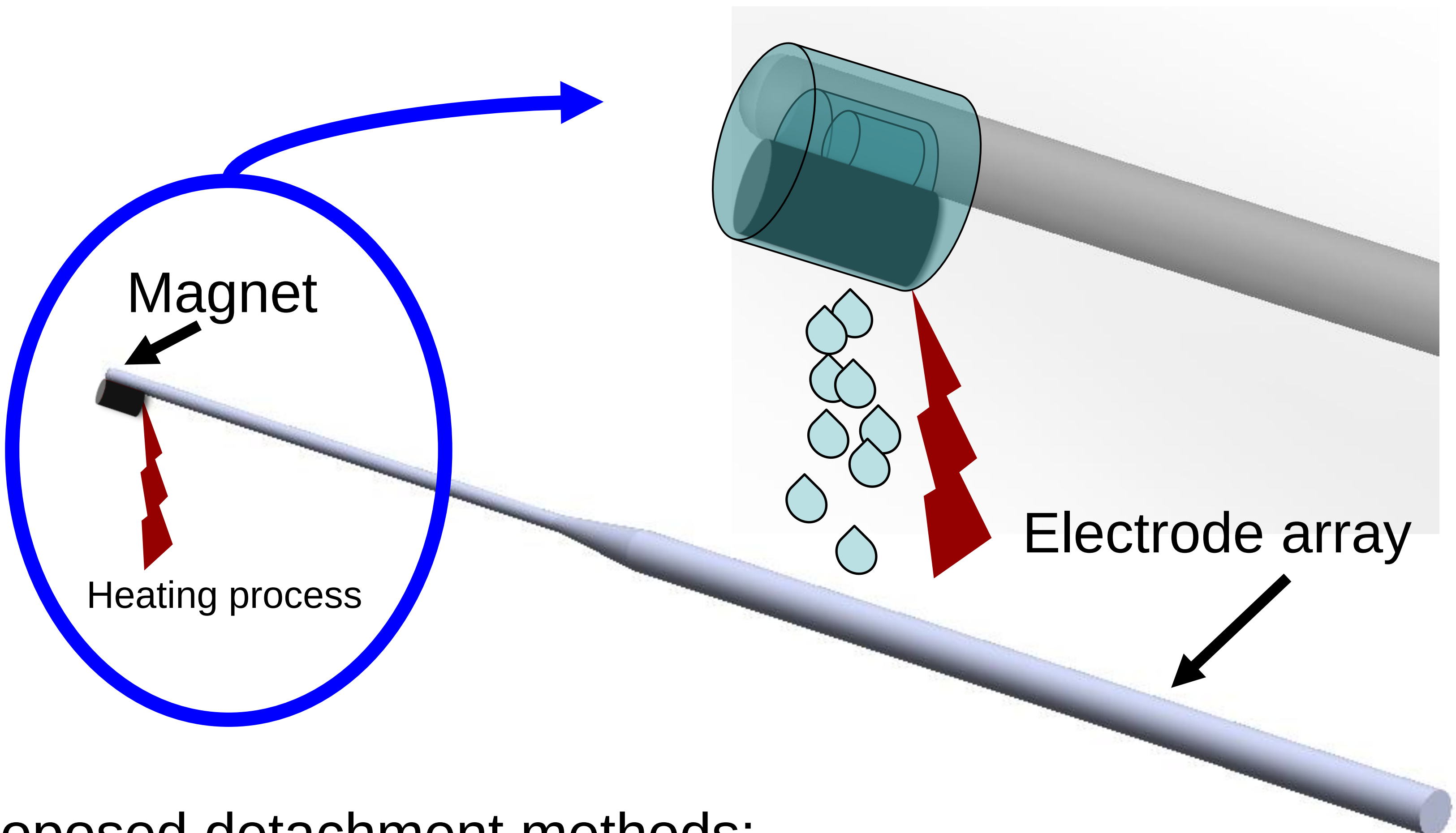
Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

Objective

What is the thermal impact of magnetic guidance of a cochlear implant?

What is the magnitude of safe range of input power to detach the magnetic tip?

Background – thermal trauma

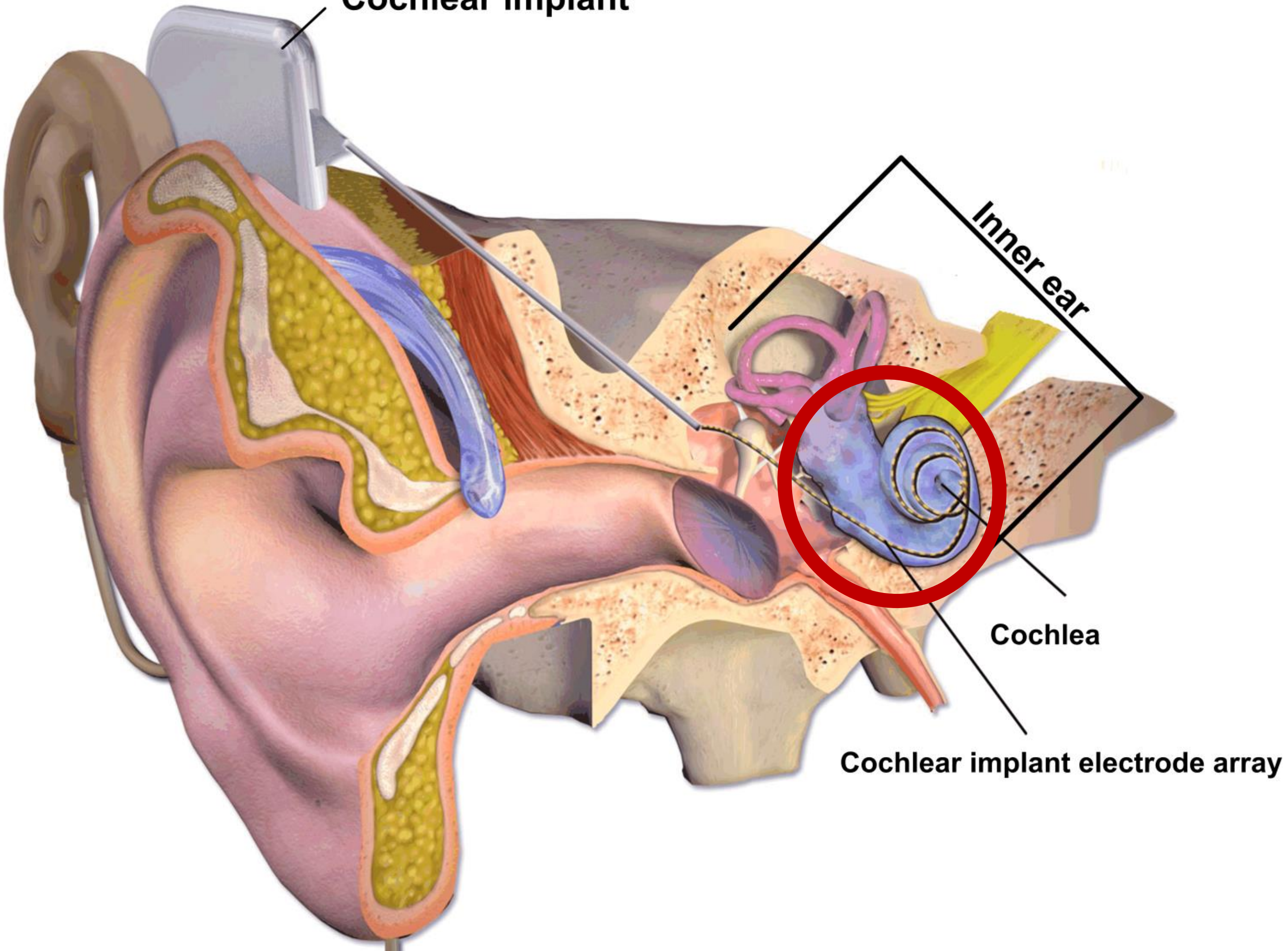


Proposed detachment methods:

- ❑ Joule heating
- ❑ Electrolysis

} Cause temperature increase

Background – ear anatomy



Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014".
WikiJournal of Medicine **1** (2). DOI:10.15347/wjm/2014.010. ISSN 2002-4436

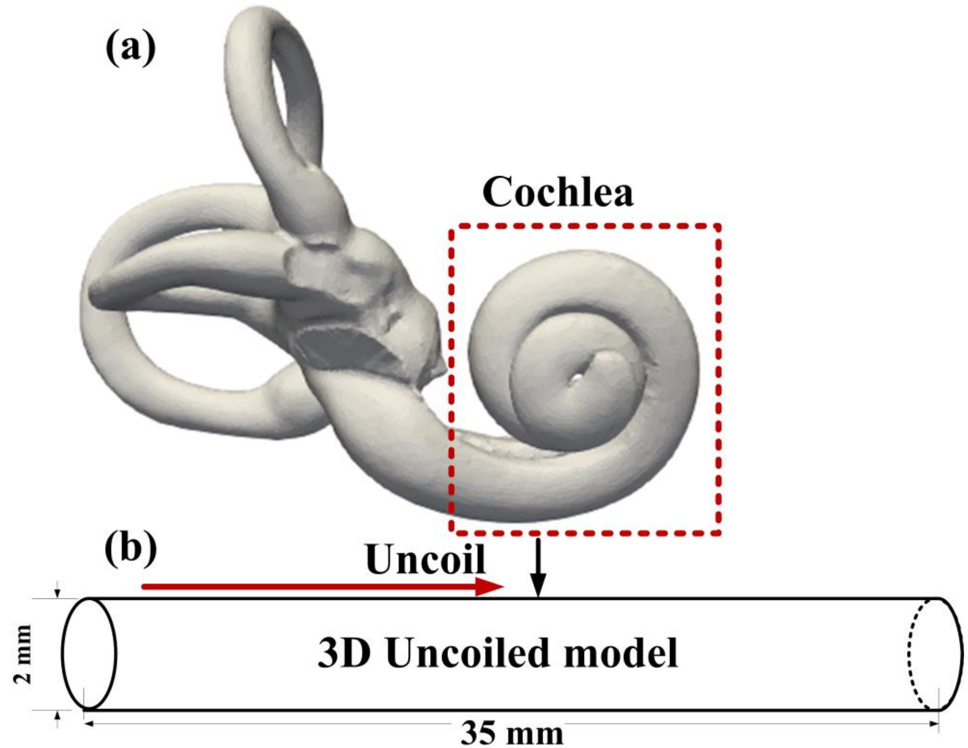
Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

Thermal dose

$$T_{tissue} < 43°C \;\; for \;\; t < 1.9\, min$$

Yoshida et al., *Journal of Neuroscience*, 1999

Objectives – uncoiled model



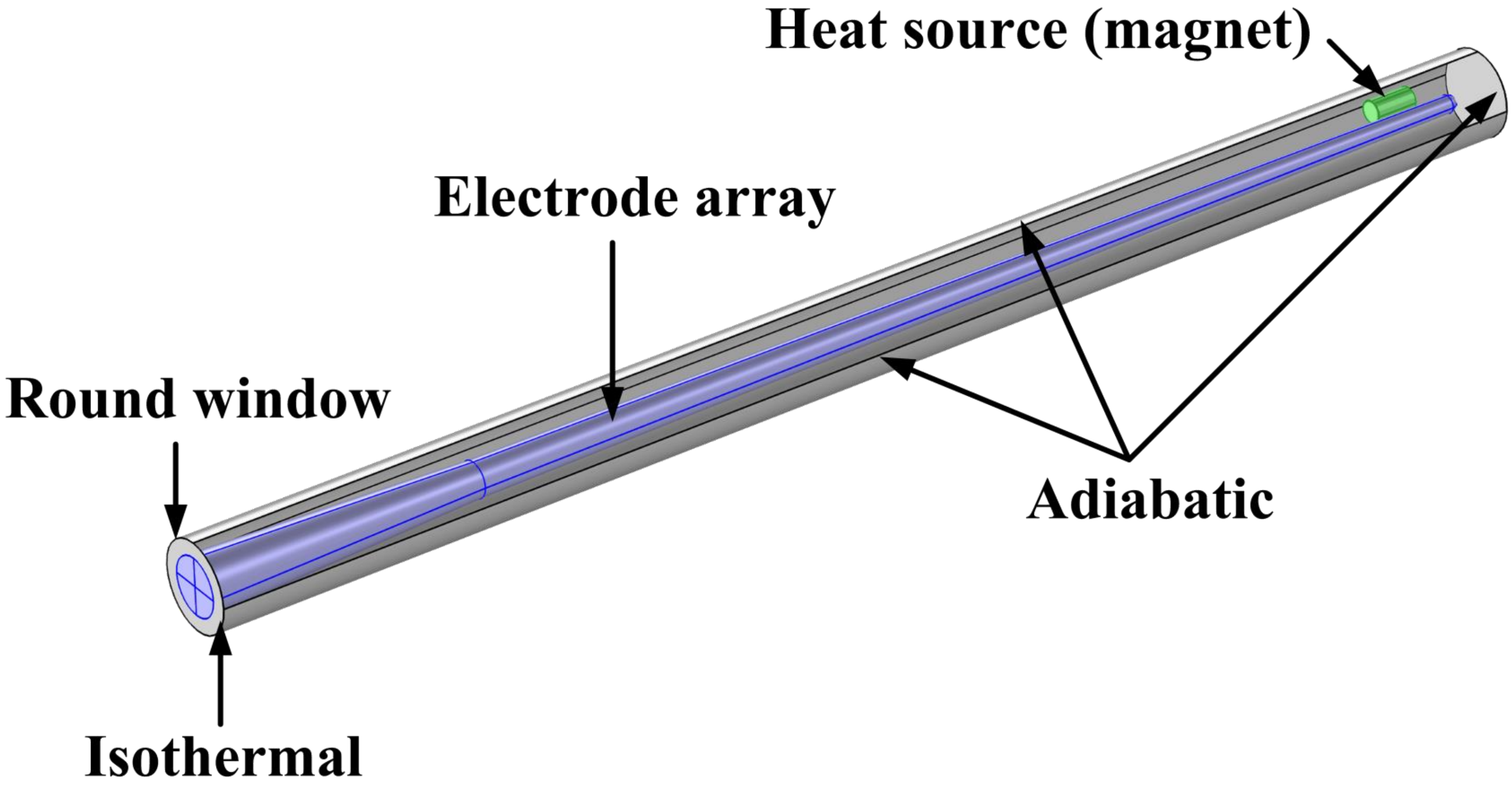
- Impact of inserted electrode array
- Impact of natural convection

(SICAS Medical Image repository http://doi.org/10.22016/smir.o.207473)

Uncoiled model of cochlea

Length 35 mm (Leon et al., *Journal of Medical devices*, 2014)

Diameter 2 mm (Biedron et al., *Otology & Neurotology*, 2010)



Data related to electrode array is provided by MED-EL

Pennes equation

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot k\nabla T + \rho_{bl} c_{p_{bl}} \omega_{bl} (T_{bl} - T) + Q_{metabolism}$$

Accumulation Diffusion Perfusion Heat generation

- Maximum input power to melt paraffin ~ 10^{-2} W
- Convective heat rate due to perfusion ~ 10^{-5} W

→ Negligible perfusion and metabolism

Solve → mass, energy, and momentum balance equations

Pennes, *Journal of applied physiology*, 1948

Scale analysis

Energy balance - magnet

$$\frac{\partial \theta}{\partial Fo} = \frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} + \frac{S L_{ct}^2}{V(T \quad T)k}$$

Accumula

Energy

$$\frac{\partial \theta}{\partial Fo} \quad \cdots \quad + \frac{\partial^2 \theta}{\partial Z^2}$$

Accumulat

Negligible natural convection

Momentum balance - perilymph

$$\underbrace{\frac{1}{Pr}\frac{\partial V_z}{\partial Fo} + Gr^{0.5}\left(V_x \frac{\partial V_z}{\partial X} + V_y \frac{\partial V_z}{\partial Y} + V_z \frac{\partial V_z}{\partial Z}\right)}_{\text{Inertia}} = -\underbrace{\left(\frac{\partial^2 V_z}{\partial X^2} + \frac{\partial^2 V_z}{\partial Y^2} + \frac{\partial^2 V_z}{\partial Z^2}\right)}_{\text{Friction}} + \underbrace{Gr^{0.5}\theta}_{\text{Buoyancy}}$$

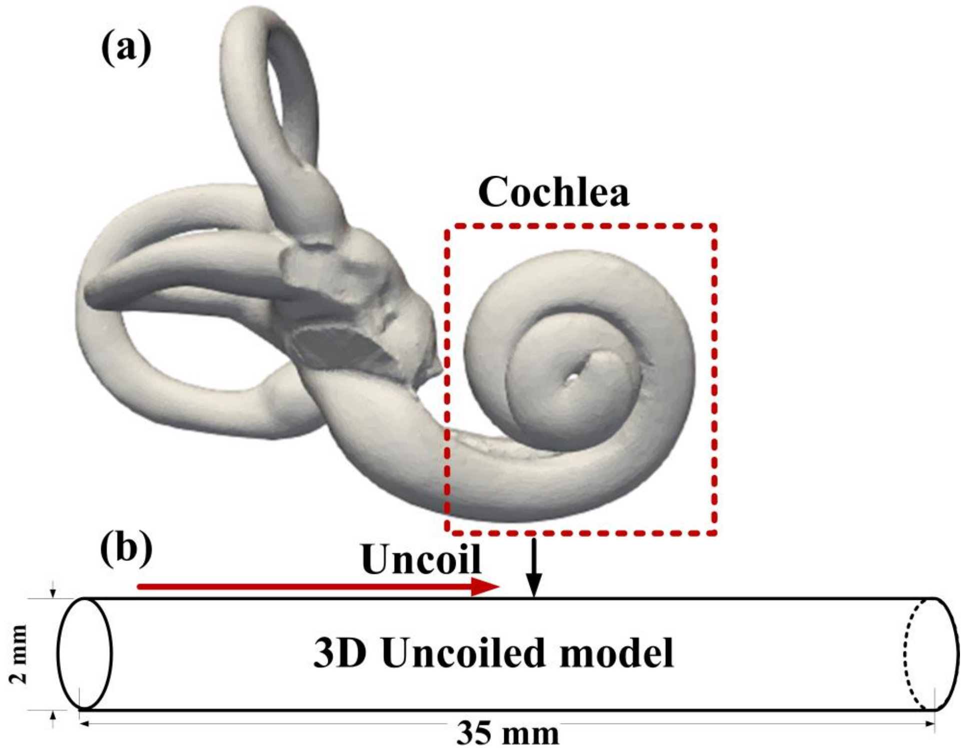
COMSOL - conduction

- **Model wizard** : 3D
- **Physics** : heat transfer in solids (ht) – Magnet (Solid), Perilymph (fluid)
  Study : time dependent → setting → times : range(0,0.01,1), range(1,0.1,114)
  Time-dependent solver → setting → time stepping → steps taken by solver → **Strict**
- **Mesh:** number of elements →142353

COMSOL – conduction + natural convection

- **Model wizard** : 3D
- **Physics** : heat transfer in solids (ht) + laminar flow (spf)
  Study : time dependent → setting → times : range(0,0.01,1), range(1,0.1,114)
  Time-dependent solver → setting → time stepping → steps taken by solver → **Strict**
- **Mesh:** number of elements →3567405

Objectives – uncoiled model



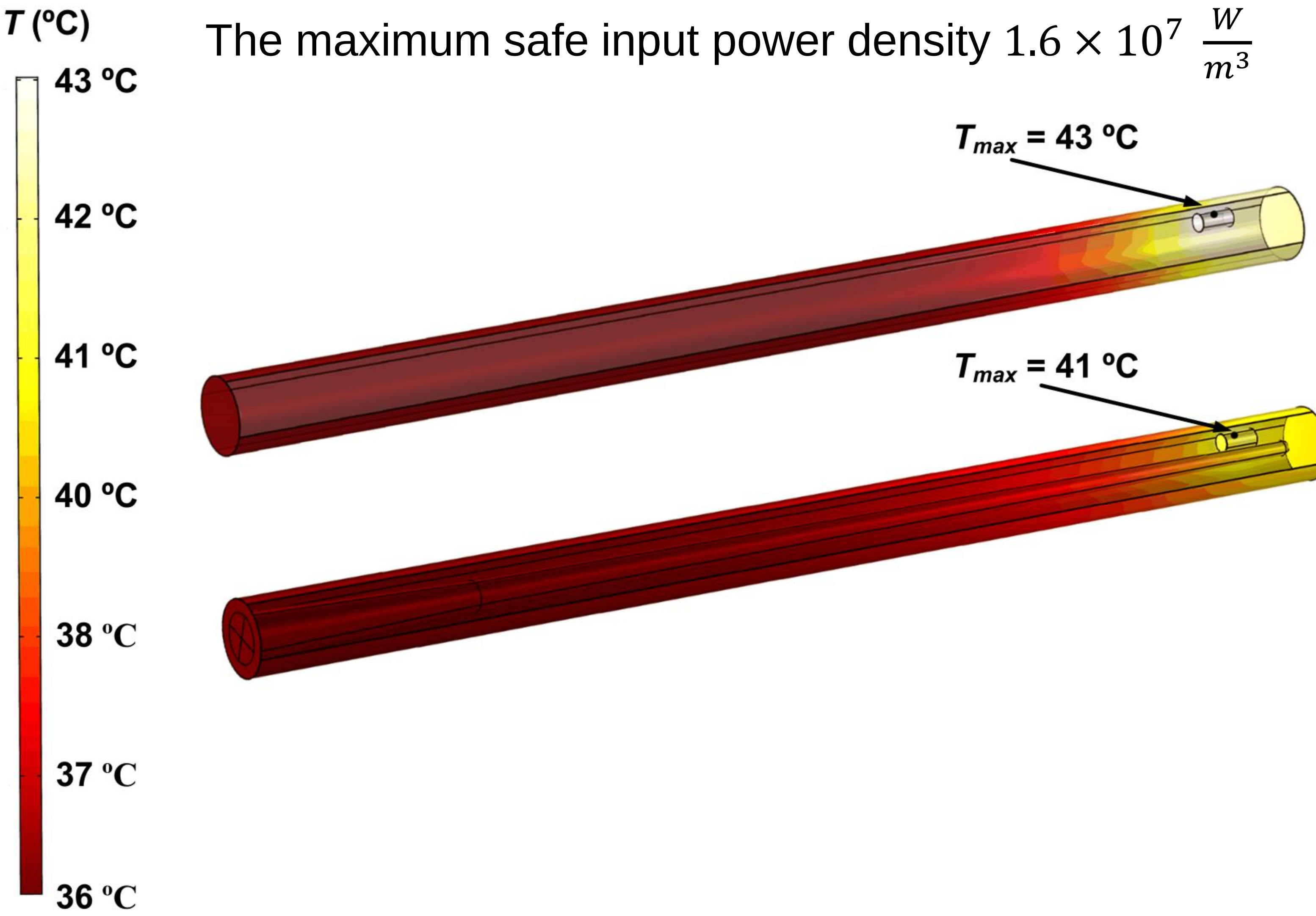
- **Impact of inserted electrode array**
- Impact of natural convection

(SICAS Medical Image repository http://doi.org/10.22016/smir.o.207473)

Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

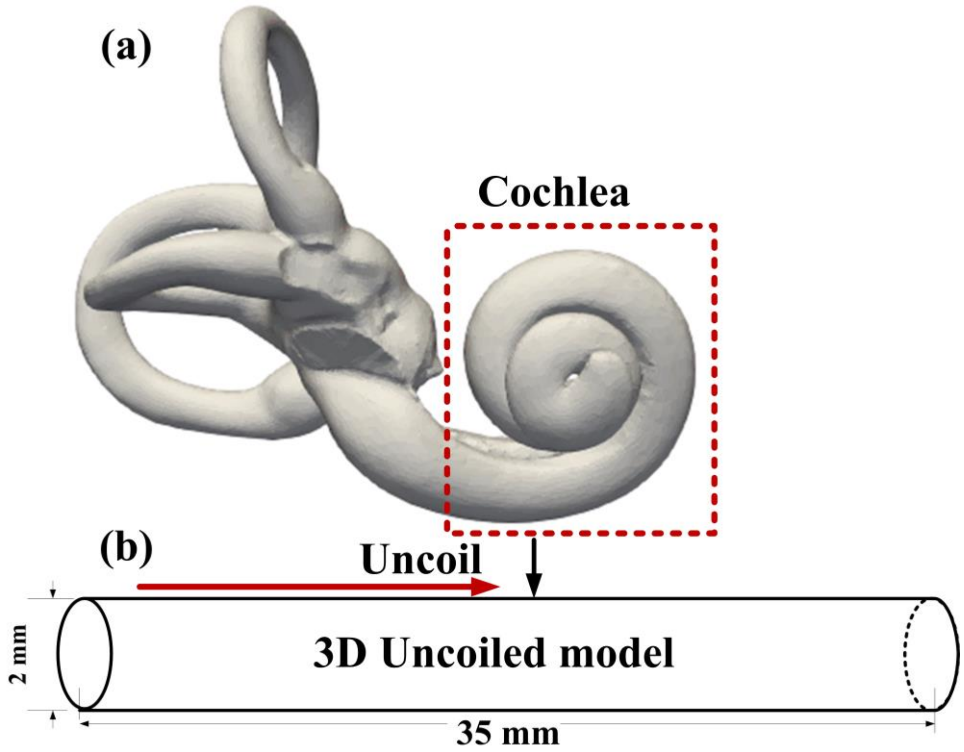
Impact of inserted electrode array

The maximum safe input power density $1.6 \times 10^7 \; \frac{W}{m^3}$



F. Esmailie, M. Francoeur, T. Ameel (to be submitted in *International Journal of Heat and Mass Transfer*, 10/2019)

Objectives – uncoiled model



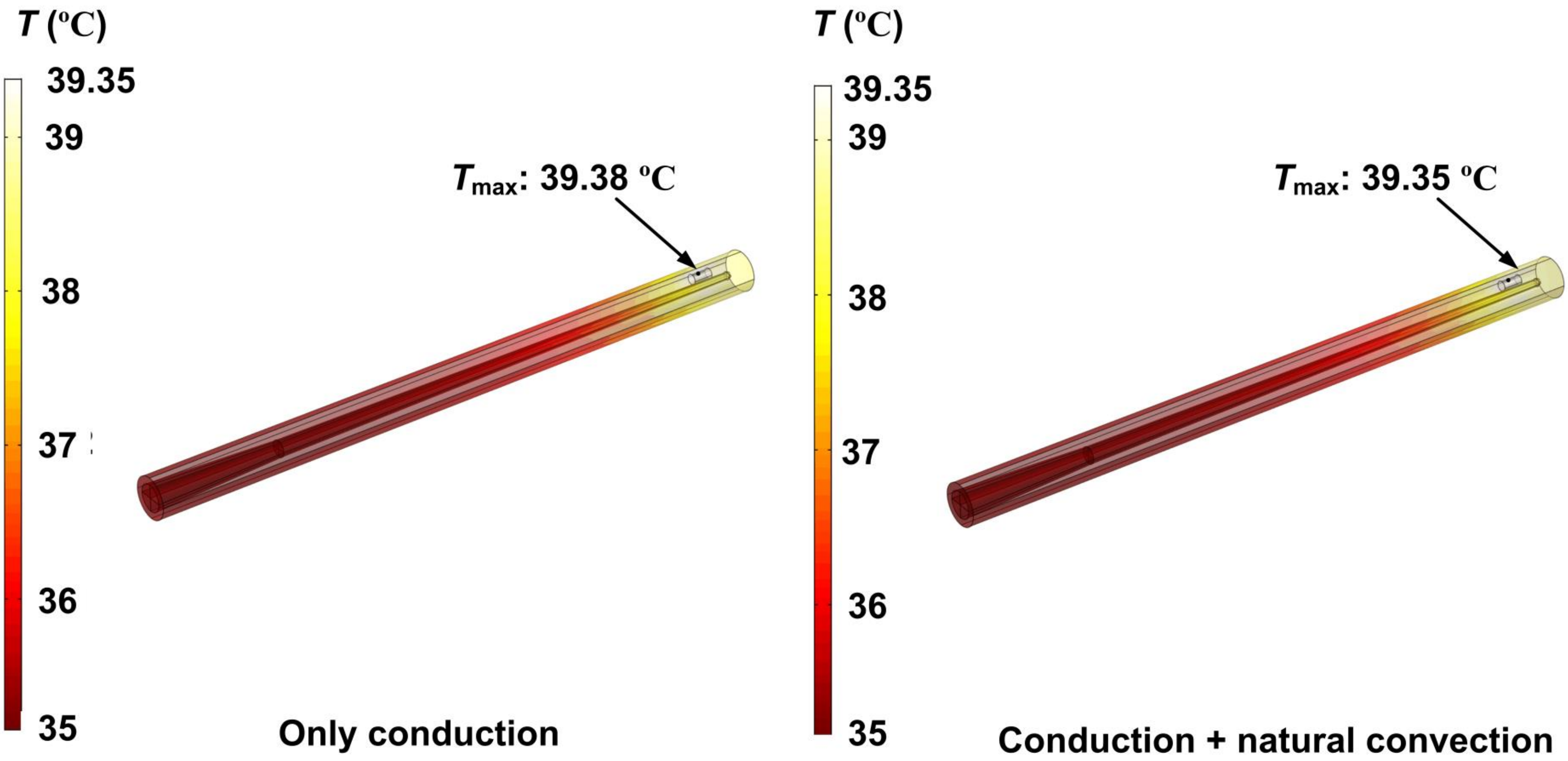
- Impact of inserted electrode array
- **Impact of natural convection**

(SICAS Medical Image repository http://doi.org/10.22016/smir.o.207473)

Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

Impact of natural convection

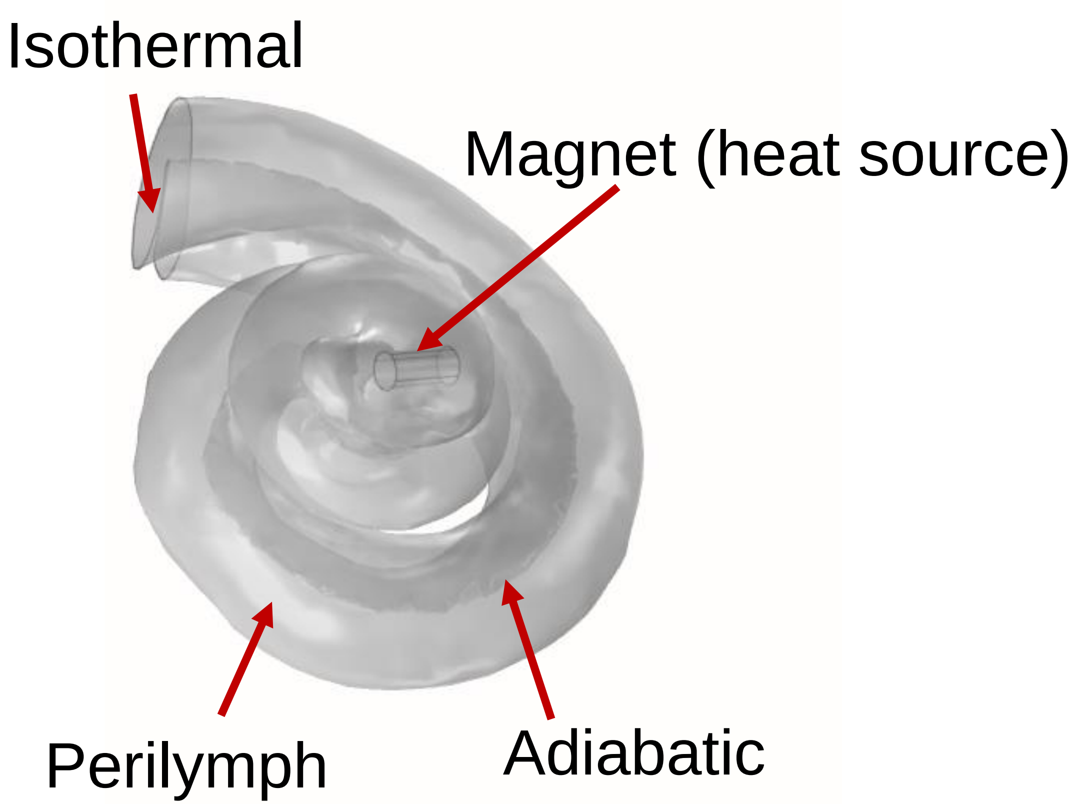
The maximum safe input power density $1.6 \times 10^{7}\ \frac{W}{m^3}$

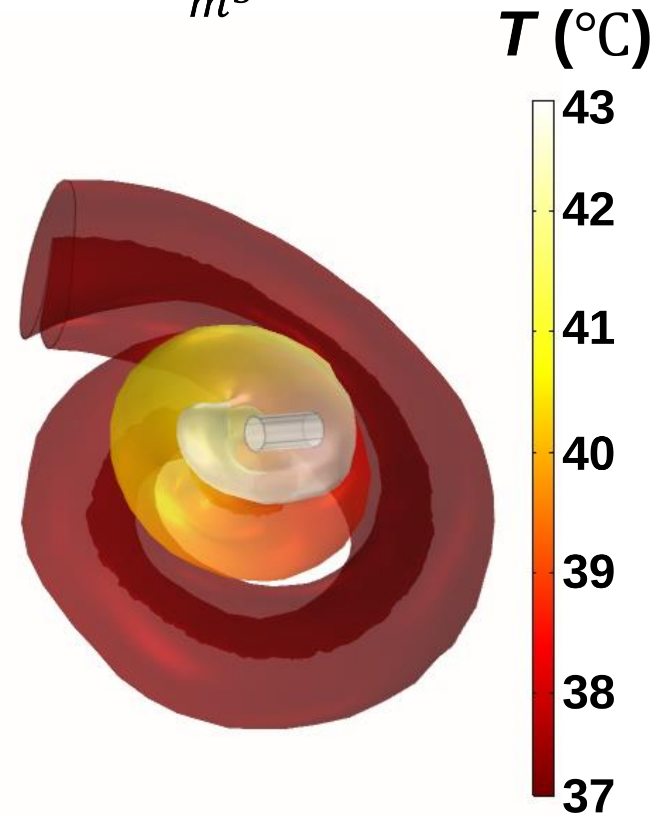


Negligible natural convection

Preliminary results on cochlea geometry

- Initial temperature = 37℃
- Neglected natural convection
- Maximum safe input power density $1.3 \times 10^{7}\ \frac{W}{m^{3}}$





(SICAS Medical Image repository http://doi.org/10.22016/smir.o.207473)

Future research

- **Add more geometrical details**

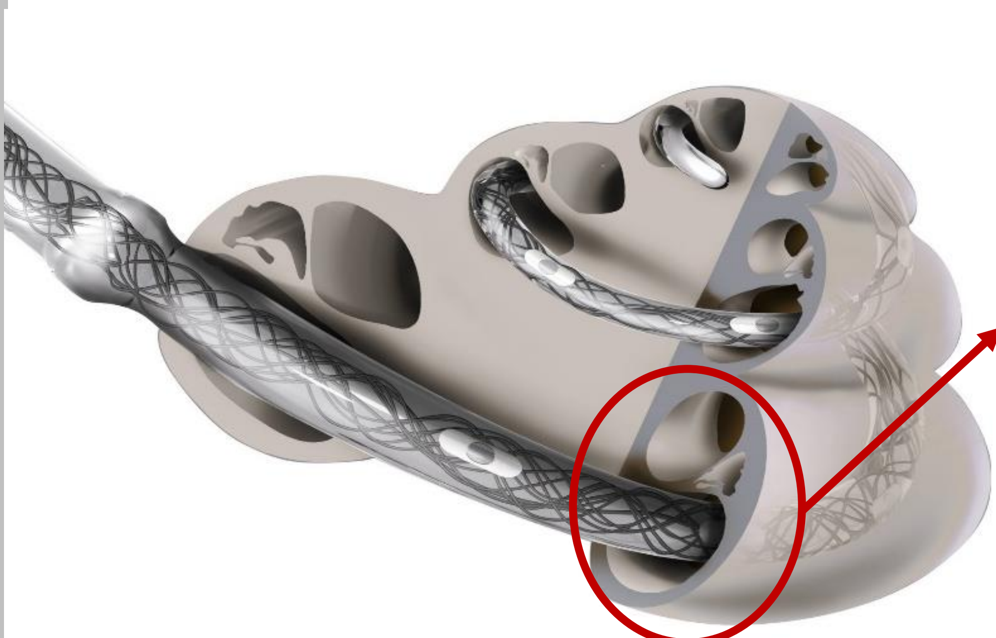
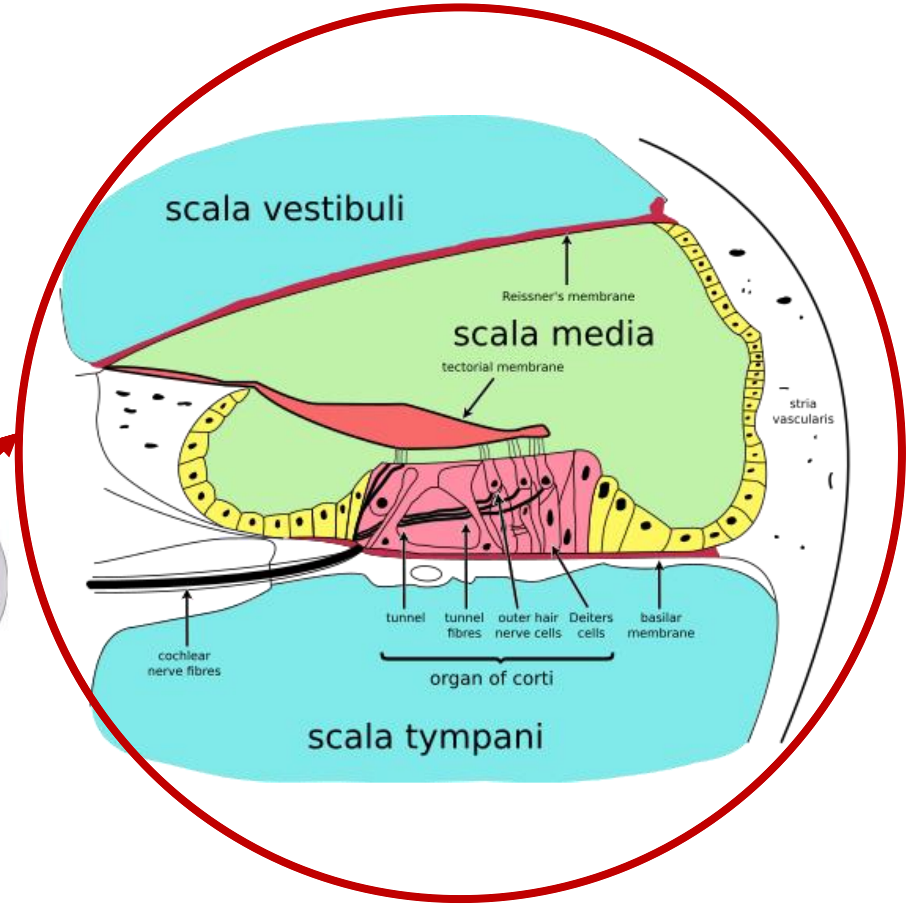


Photo by MED-EL (used by permission)



https://commons.wikimedia.org/wiki/File:Cochlea-crosssection.svg

Acknowledgment

- Professor Tim Ameel
- Professor Mathieu Francoeur

- The National Institutes of Health (NIH)
  Award Number: R01DC013168
- Department of Mechanical Engineering, University of Utah

Question?

- Fateme.esmailie@utah.edu

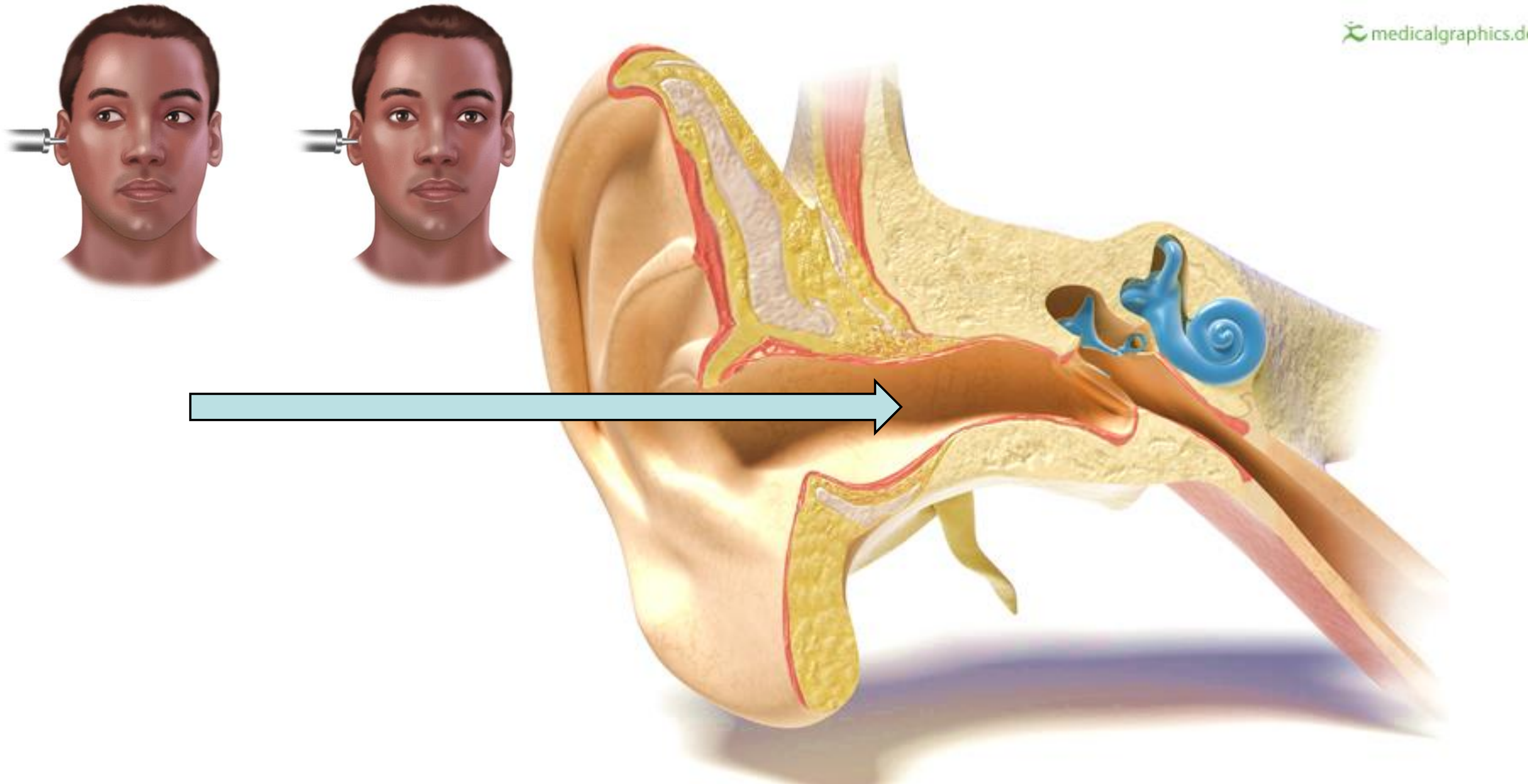
Questions?

$$\frac{k_{eff}}{k} = 0.386\left(\frac{Pr}{0.861 + Pr}\right)^{0.25} Ra^{0.25}$$

$$k_{eff}/k = 0.76$$

Samples

Caloric test

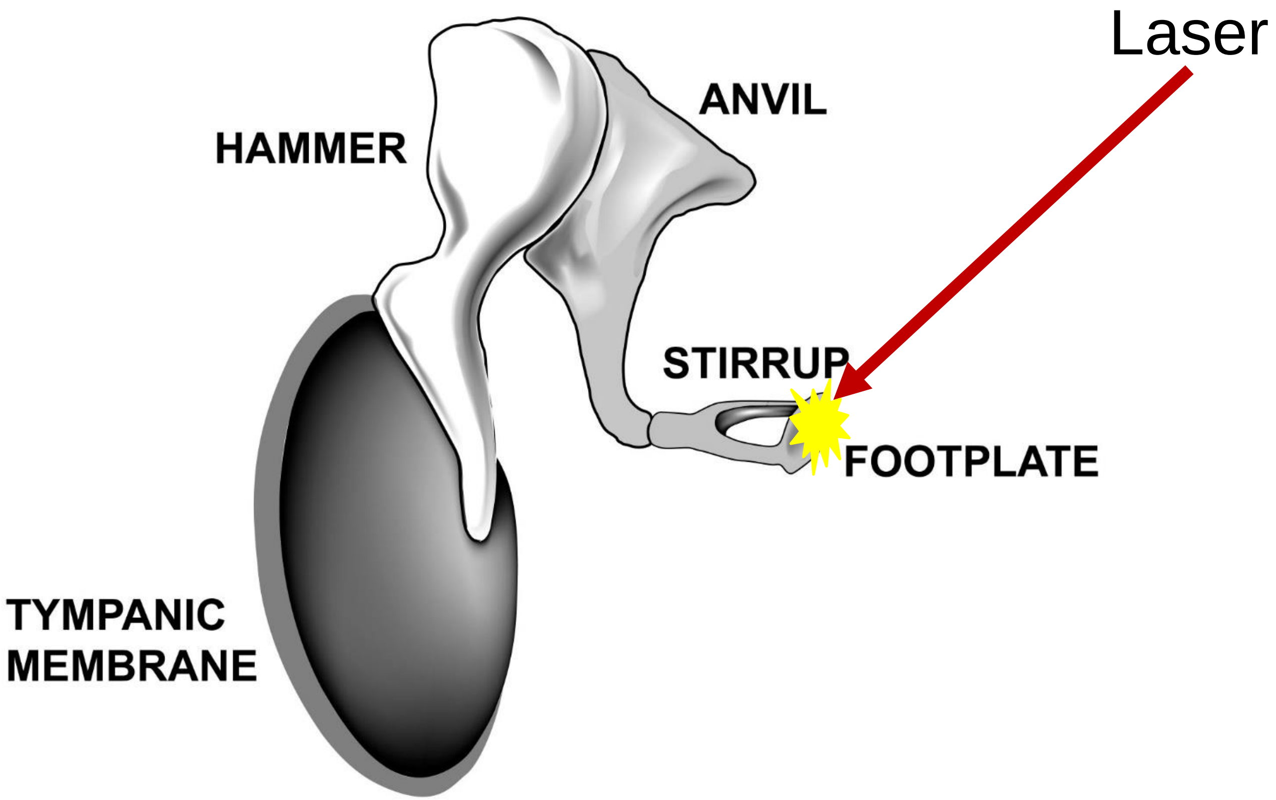


Maximum temperature change = 1° C

Department of Mechanical Engineering
COLLEGE OF ENGINEERING | THE UNIVERSITY OF UTAH

Stapedectomy

Maximum temperature change = 2.9° C

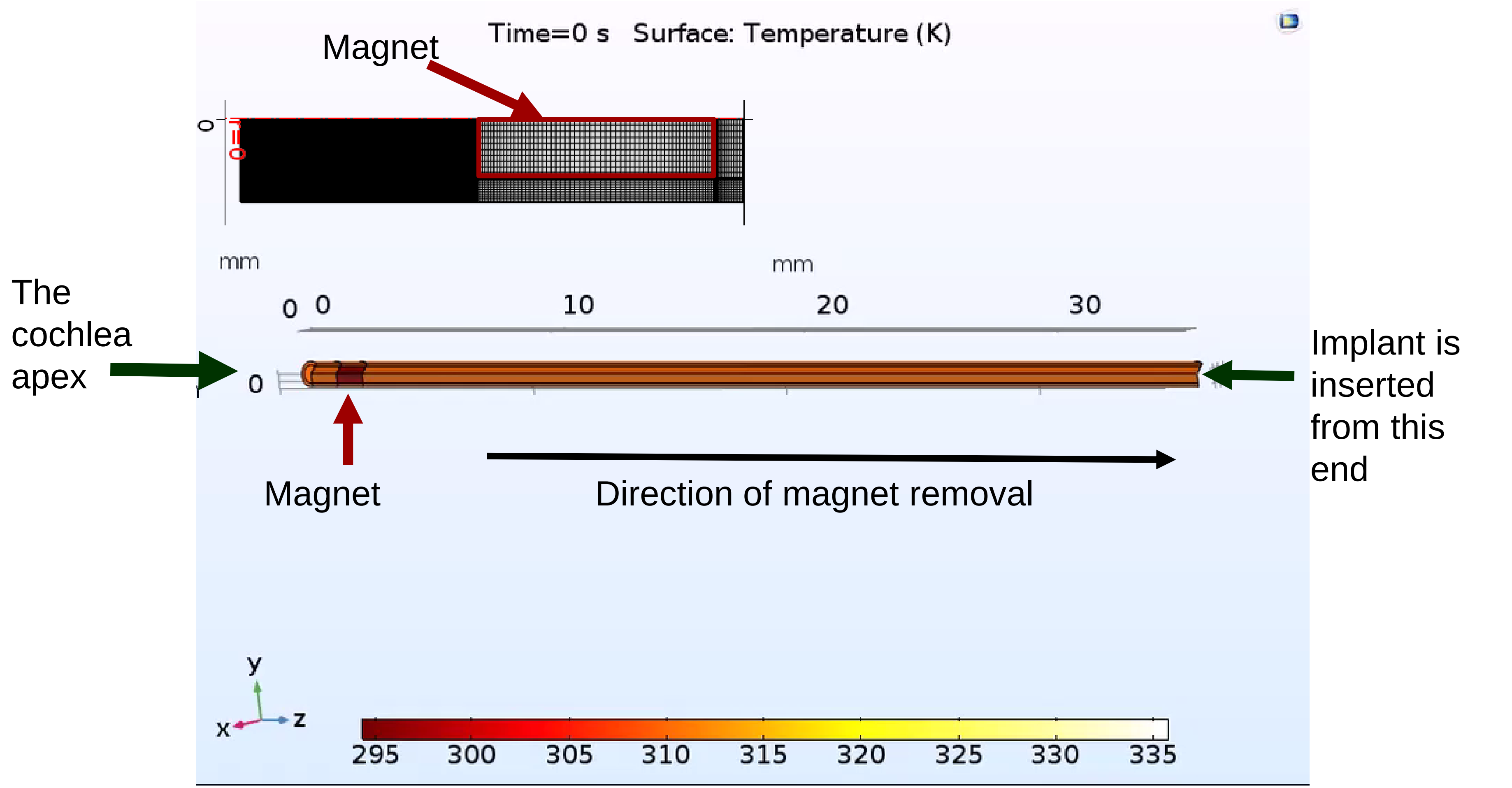


No permission yet

https://www.psywww.com/intropsych/ch04-senses/auditory-system.html

Future work

- Heat transfer in fluid + moving mesh (ale)

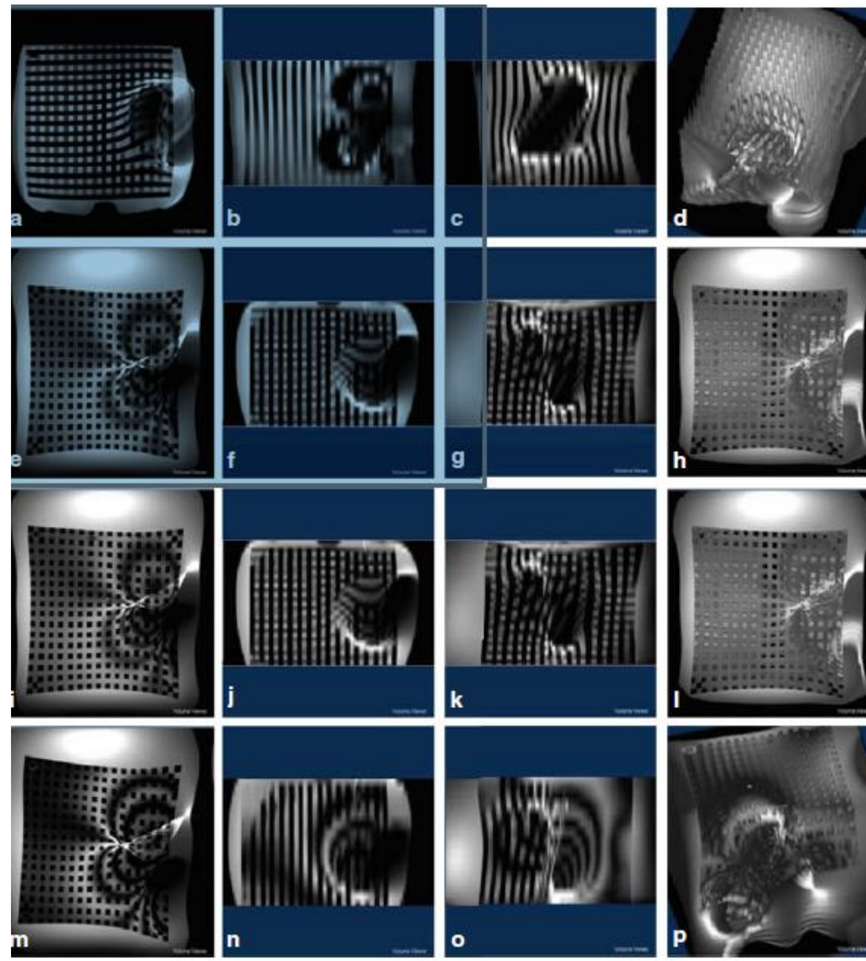


Literature review – MRI effect

Majdani *et al.*, 2008

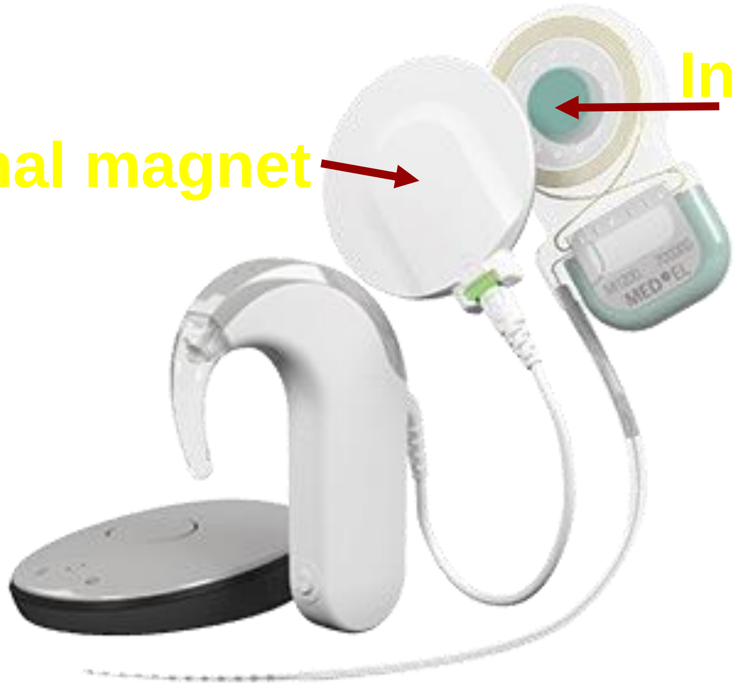
Maximum temperature change = 0.5° C

Wang et al., 1998
Majdani *et al.*, 2008



Majdani *et al.*, 2009

Background – Cochlear implant



Model description

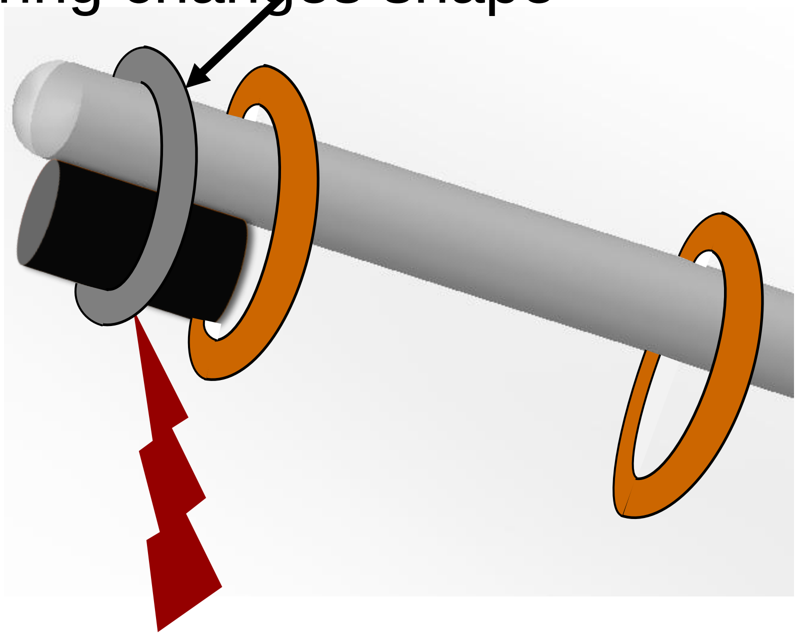
- Software : MATLAB R2016a
- Solver: ode45
- Time step: 0.5 s
- Input data:

  1. Initial condition: Ambient temperature

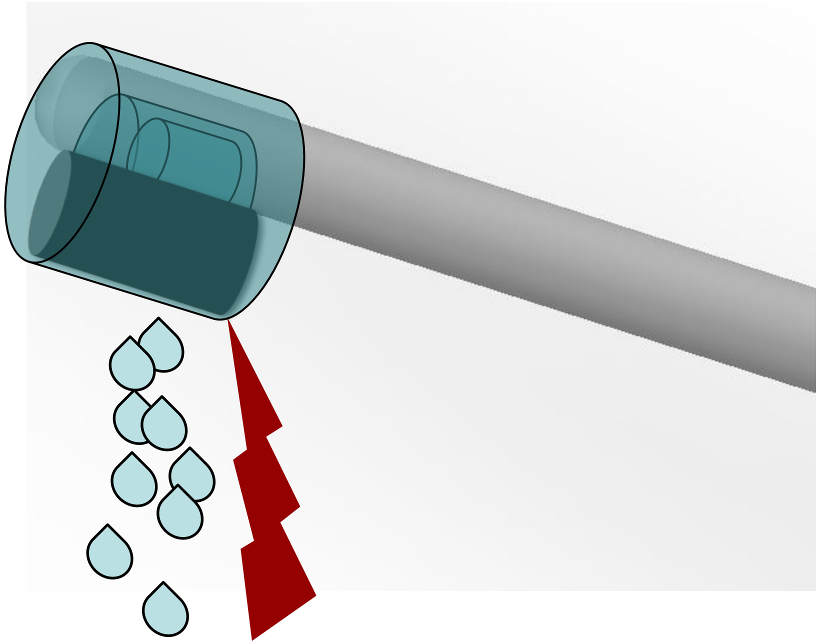
  2. Input current
- Output data:

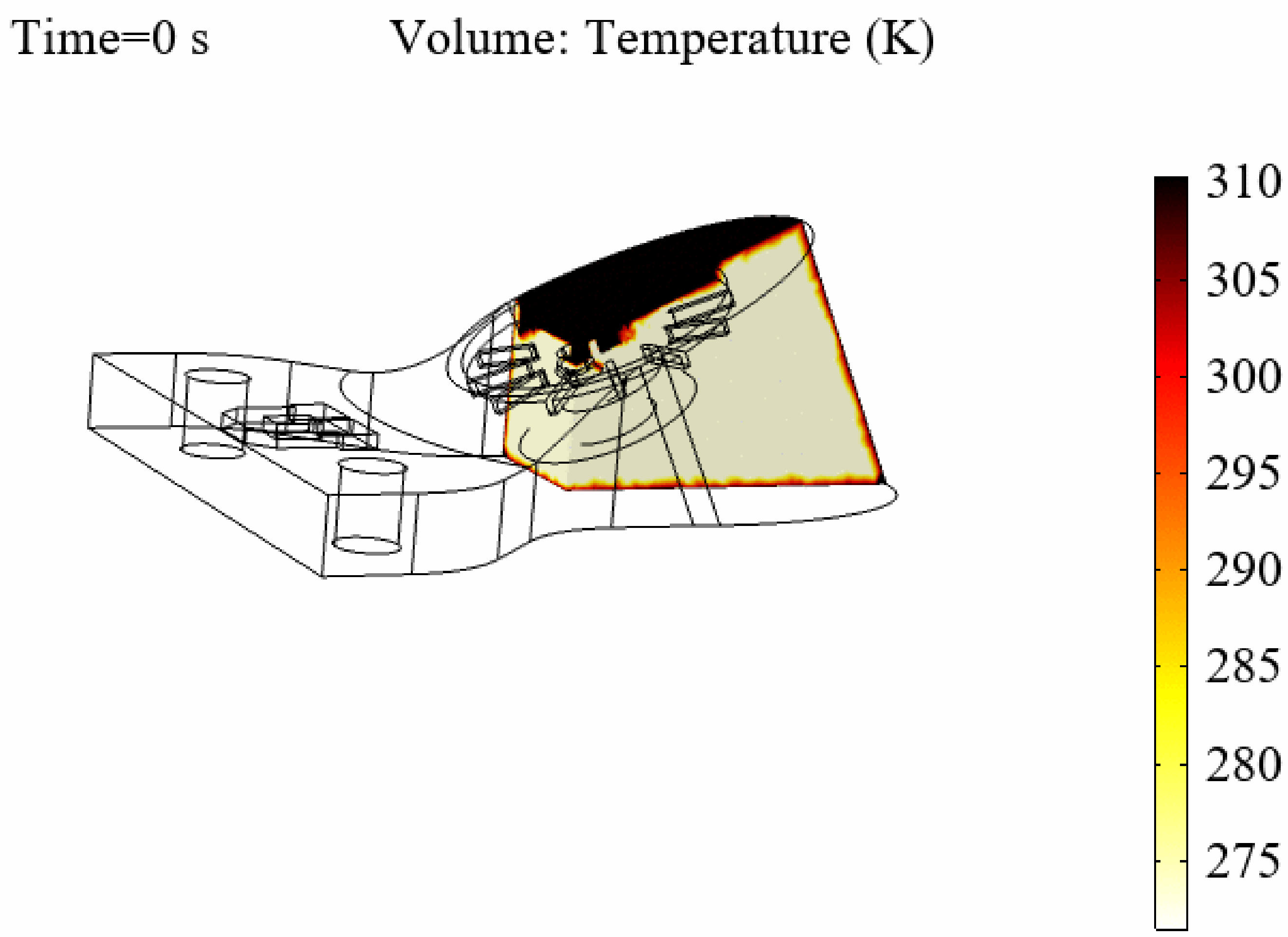
  Components' temperatures with respect to time

Magnet removal – shape memory alloy



Magnet removal – adhesive




Time=0 s
Volume: Temperature (K)
310
305
300
295
290
285
280
275