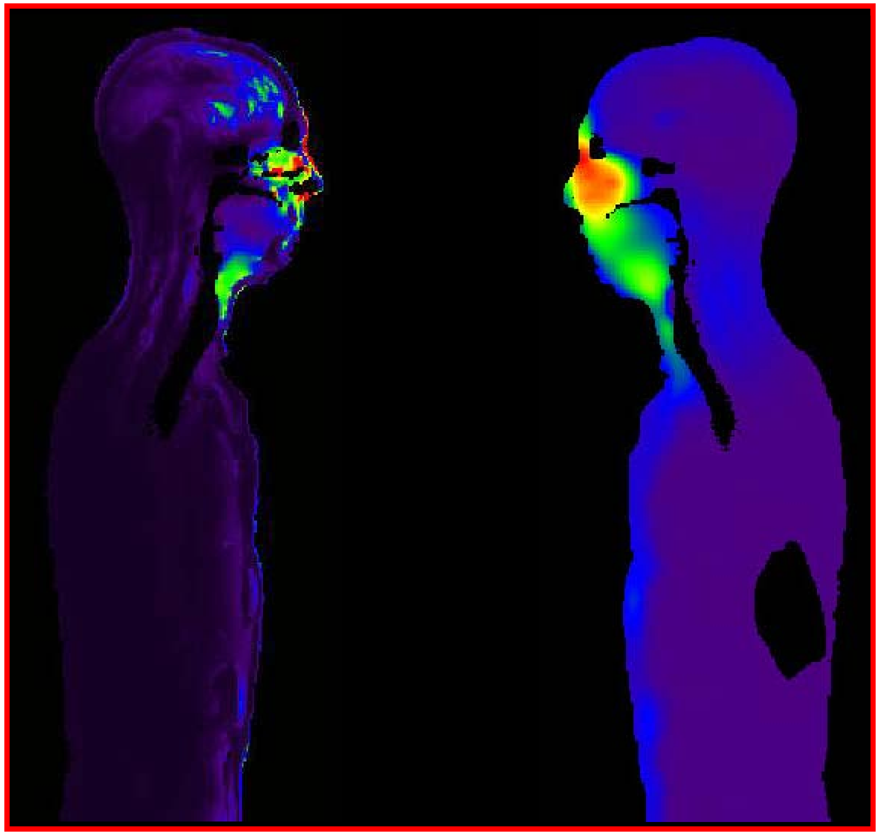
Correlation between SAR and temperature in different tissues



Robert McIntosh & Vitas Anderson

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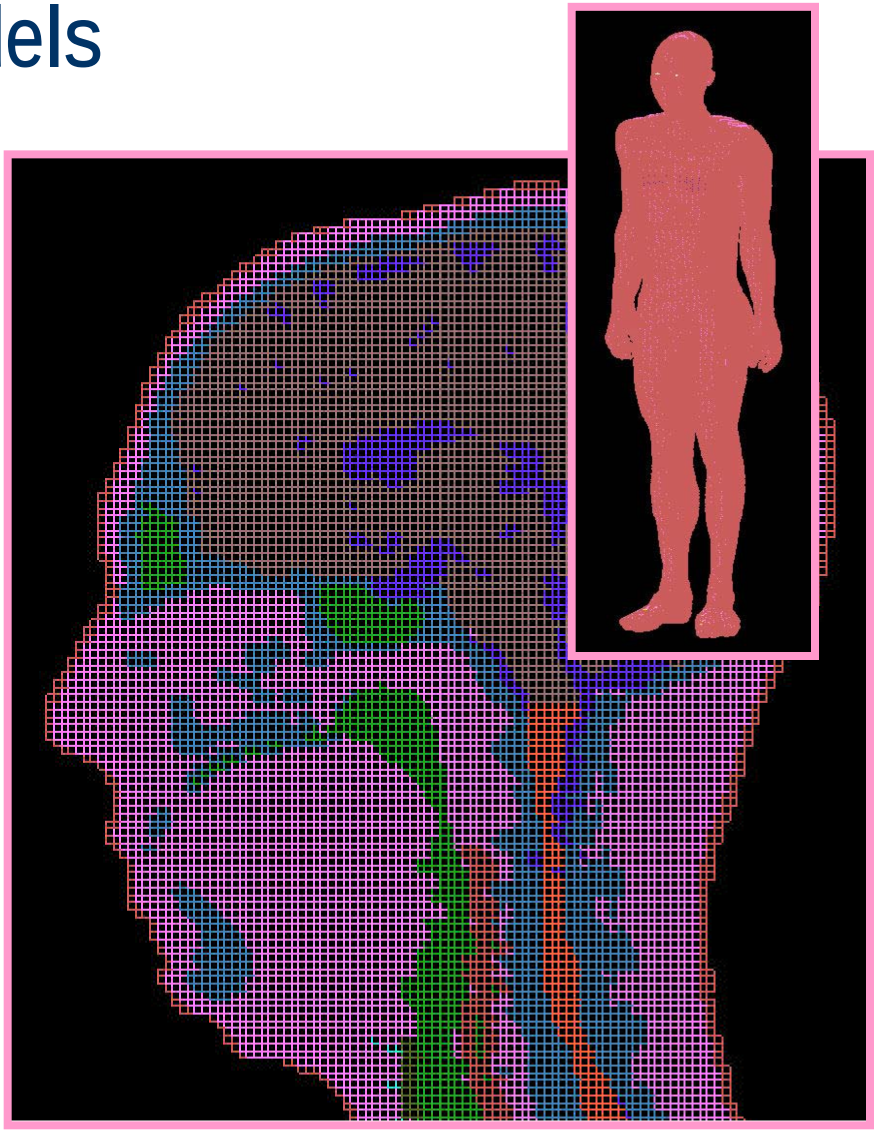
Australian Centre for RF Bioeffects Research

SWINBURNE UNIVERSITY OF TECHNOLOGY

Human body numerical models

- Discretise tissues into cells & assign tissue properties
- Electromagnetic:
  - electrical conductivity (σ)
  - permittivity (ε_r)
- Thermal:
  - thermal conductivity (k)
  - specific heat capacity (c)
  - blood flow (m)
  - metabolic heat production (A_0)
- Density (ρ) and water content (w)

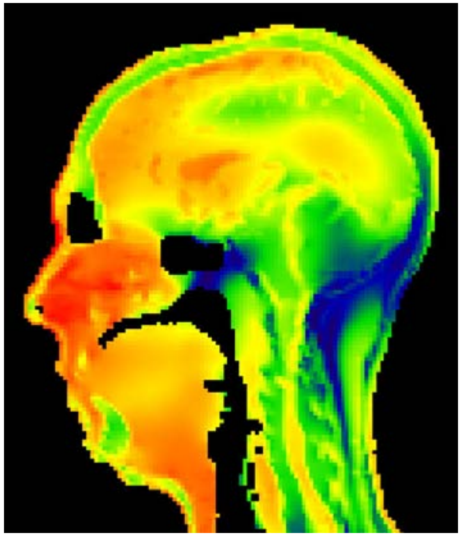


2-D slice of 3-D model

('Norman' courtesy UK-HPA)

Electromagnetic modeling

- *E*-field & Specific energy Absorption Rate (SAR)
- SAR (W/kg) is a metric for specifying RF exposure
  - 100 kHz – 10 GHz in ICNIRP 1998 Guidelines
  - 100 kHz – 3 GHz in IEEE 2005 Standards
- Defined as the rate of energy absorbed by a mass



SAR for 1 GHz plane wave exposure

$$SAR = \frac{\sigma |E|^2}{\rho}$$

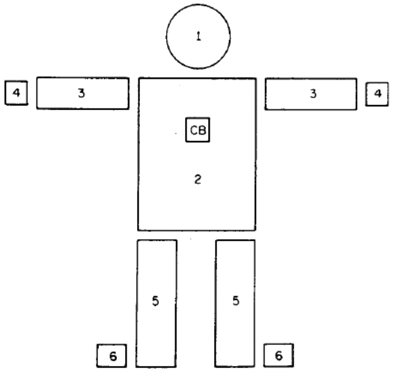
where

E is the *E*-field (V/m)

σ is the conductivity (S/m), and

ρ is the mass density (kg/m^3)

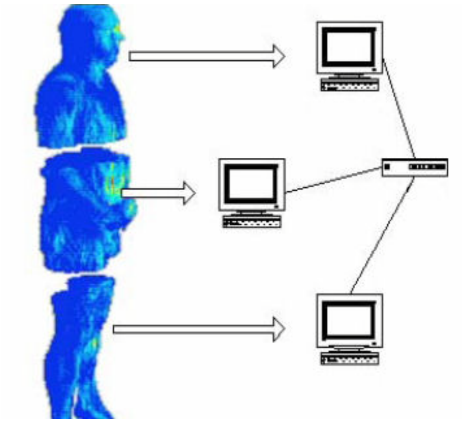
Thermal modeling



Hardy-Stolwijk Model, 1979

Pennes' bio-heat equation

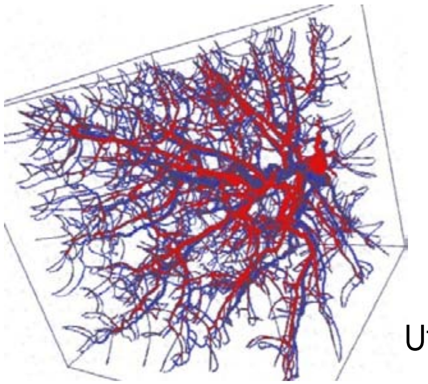
- Treat blood flow as a general heat sink term
- Add thermoregulatory effects
- Pennes' equation sufficient to examine localised RF exposures at the safety limits
- Eleanor Adair found good match with measurements for high exposure for whole body



Nelson et al.
U. So. Alabama & Brooks AFB

Full treatment of localised vascular system

- Includes heat exchange between vessel and tissue
- Hyperthermia and tumour research



Lagendijk et al.
Utrecht, The Netherlands

Tissue thermal properties database

- Accurate analyses require reliable estimates of tissue properties:

  thermal conductivity (k) specific heat capacity (c)
  blood flow (m) metabolic heat production (A_0)
  density (ρ) water content (w)

- We have documented 150 key papers and books and developed a database for 44 human tissues:

  6 properties x 44 tissues = 264 values

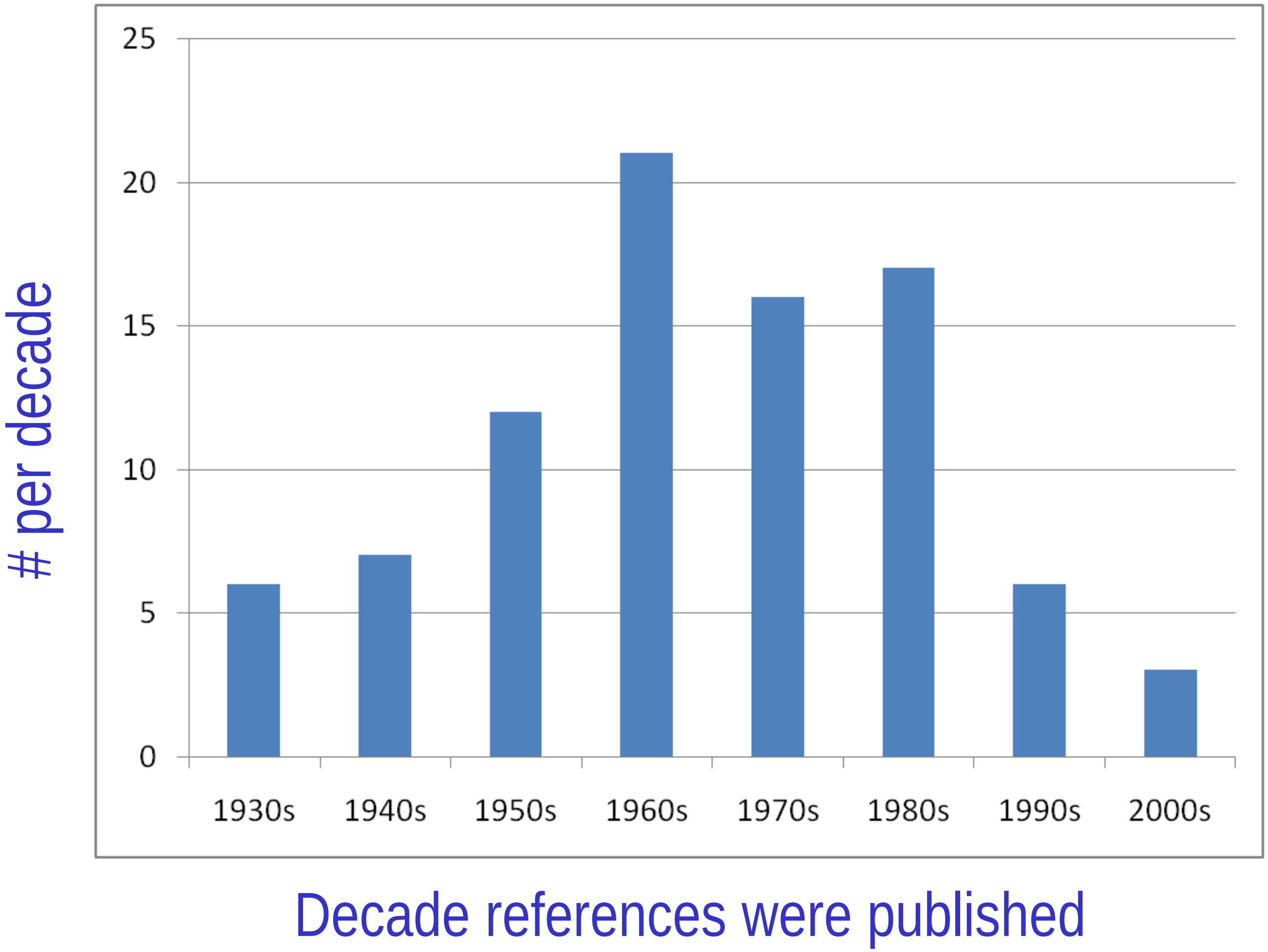
  including average, min, max, # values, & source

- Only values from original measurements are listed

Benefits of tissue properties database

- A standardised set of thermal tissue values would lead to greater consistency between modellers and those setting safety standards
- Helps consolidate the limited data there is available
- This database to be made freely available for use by those interested in biological thermal modelling

When measurements were made

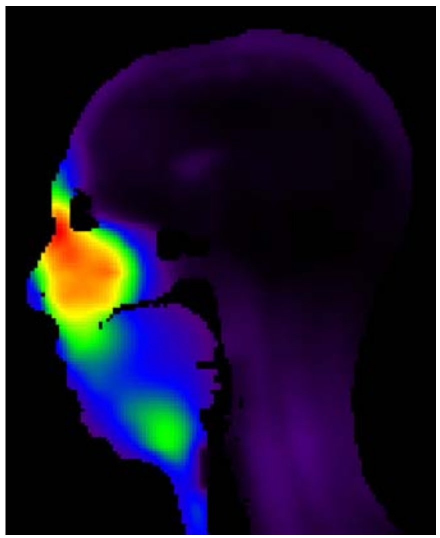


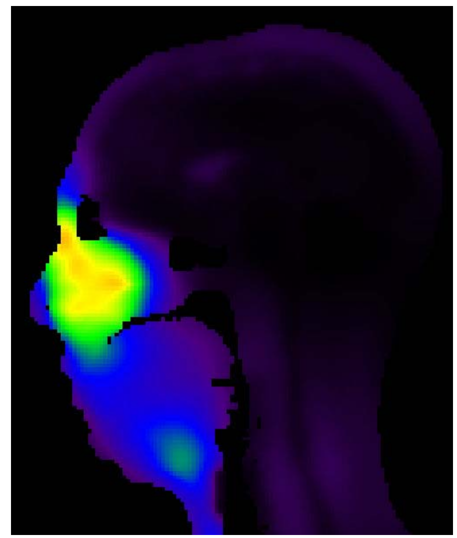
Comparison with Bernardi et al. 2003

- Test case highlights significant influence of tissue properties (especially blood flow) on ΔT
- Use average for each tissue property as input into our model

Database values

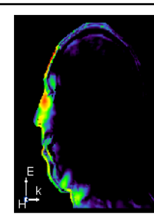
Peak ΔT: 0.10 °C





Bernardi et al. values

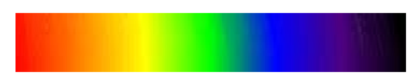
Peak ΔT: 0.075 °C



1 GHz

plane-wave

5 W/m^2



Sensitivity of ΔT to thermal conductivity (*k*) and blood flow (*m*)

- Study varied

  k +/- 10%

  m +/- 10%

- Used human body models at 0.5, 1, 3, 6, & 10 GHz
- Preliminary results show ΔT most sensitive to blood flow

  e.g. *m* +/- 10% $\Rightarrow$ ΔT +/- 8% (in brain at 1 GHz)

RF exposure limits set due to thermal effects

- RF Standards setting bodies recognise primary interaction is thermal

  "*Only mechanism of **interaction of RF energy** with the body's tissues that has been **demonstrated definitively is thermal** …*"

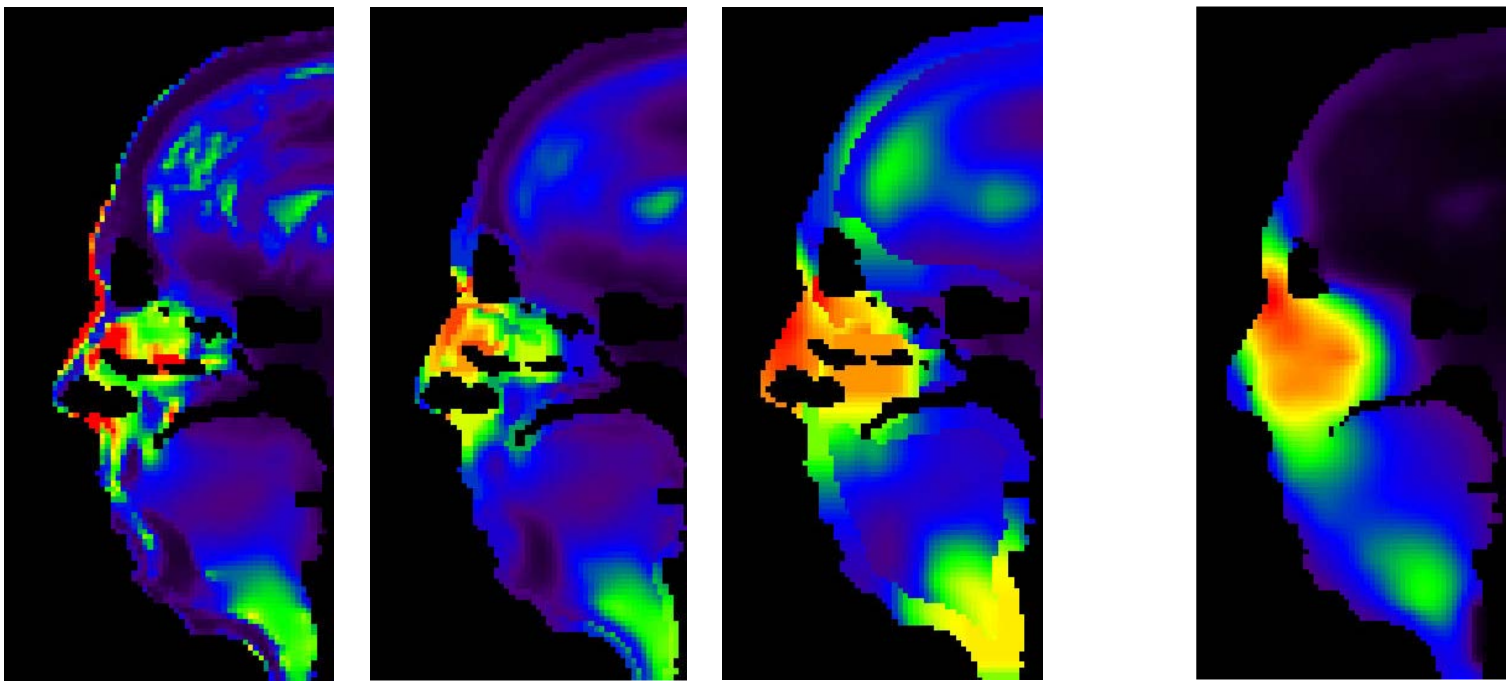
  Eleanor Adair (ICES SCC-28 SC-4 Working Group, 2001)

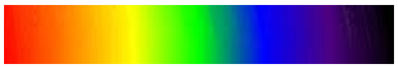
- Whole body SAR limits derived using temperature considerations
  - Animal measurements: 4 W/kg ~ 1ºC core body change
  - Public limit 0.08 W/kg (ICNIRP 1998)

Comparison SAR averaging and temperature change

- SAR is mass averaged, in recognition of thermal diffusion properties of tissues
- Highest correlation is between 7-10 g average SAR and ΔT

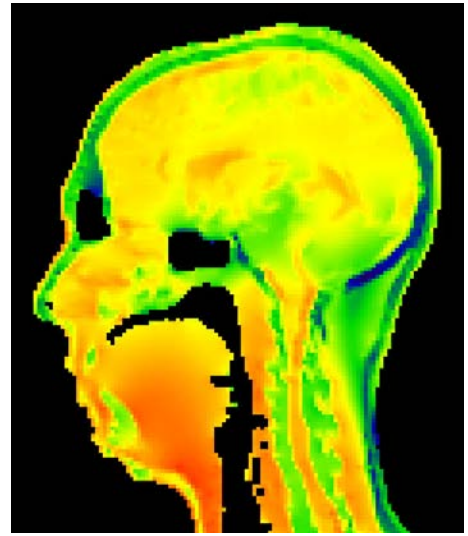
(Hirata et al. 2009, Bit-Babik et al. 2007, McIntosh et al. 2008)



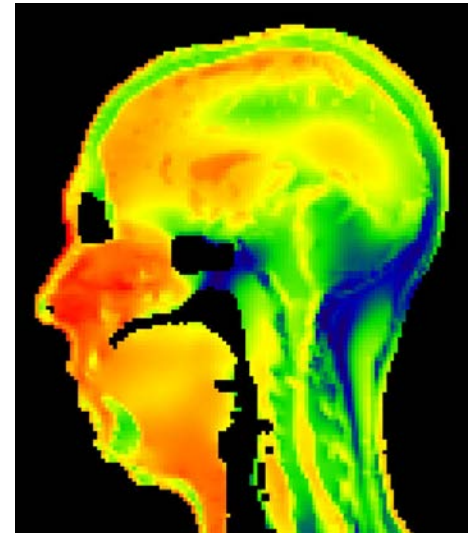


SAR at each frequency

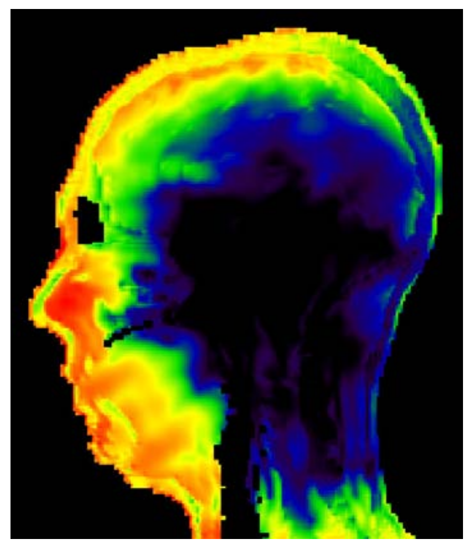
- Location changes
- As frequency increases depth of penetration decreases
- Depth will effect thermoregulatory response



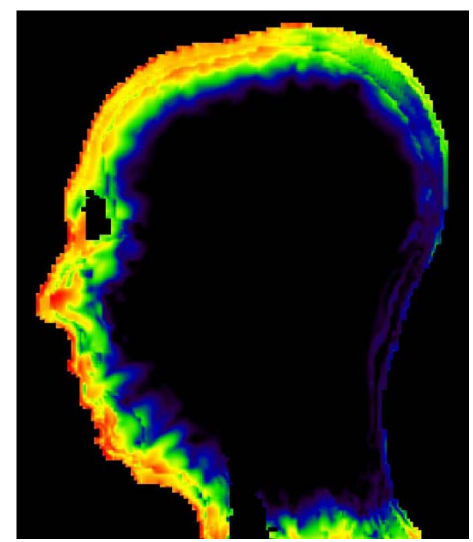
500 MHz



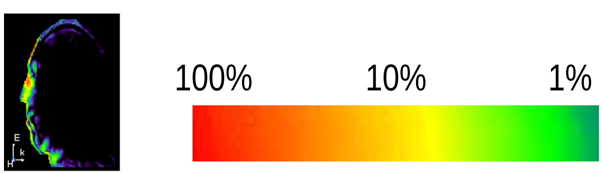
1 GHz



3 GHz



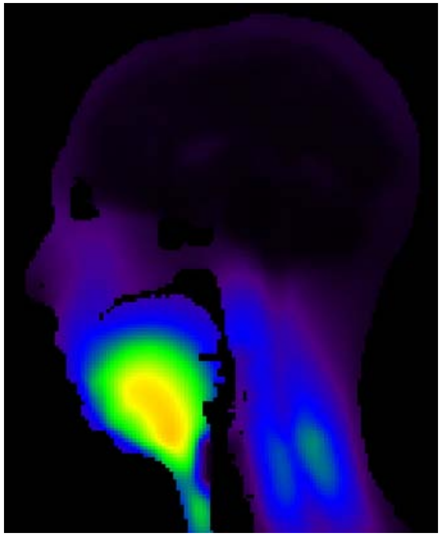
6 GHz



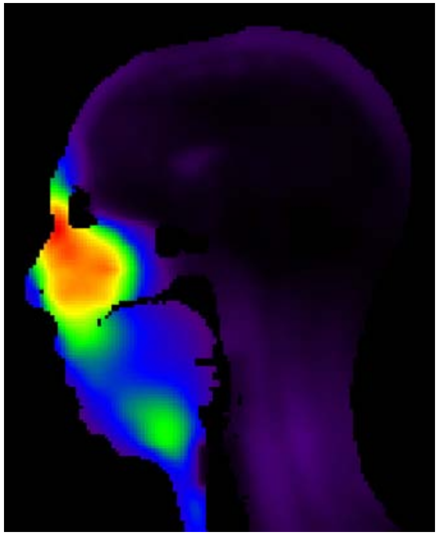
plane-wave

Thermal response, ΔT, at each frequency

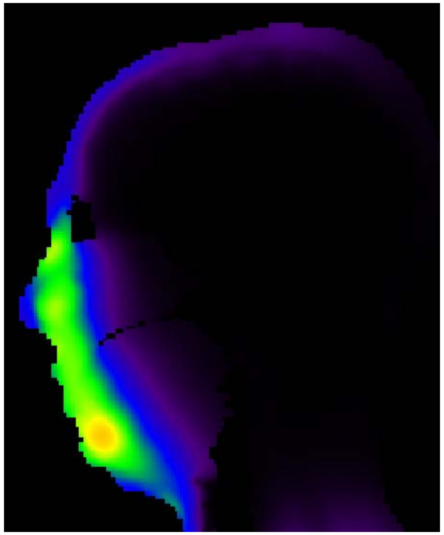
- Location changes (due to SAR)
- Negligible ΔT for internal tissues as frequency increases



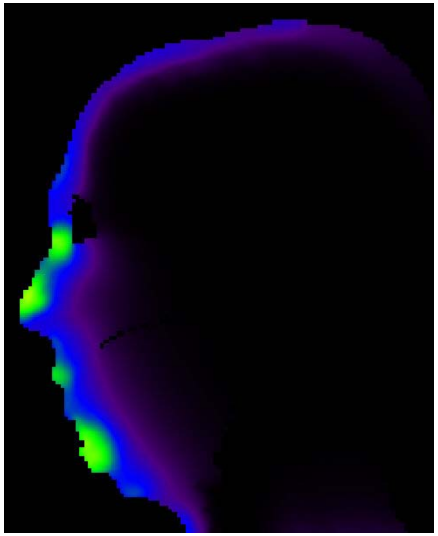
500 MHz



1 GHz



3 GHz



6 GHz

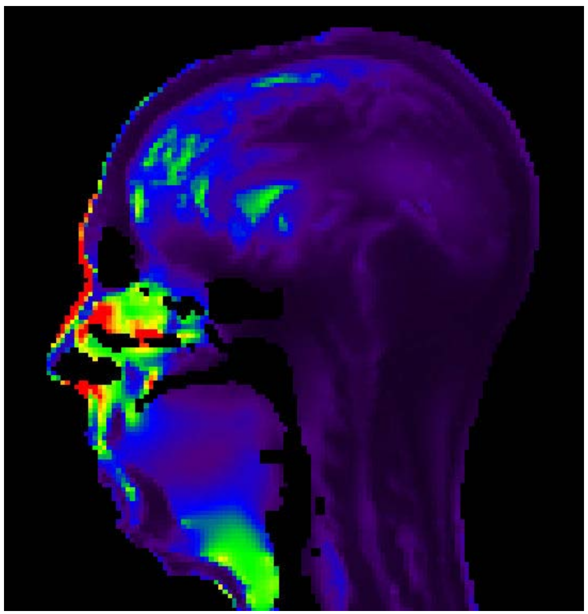
ΔT

(peak ΔT = 0.1 °C at 5 W/m^2)

100% 50% 0%

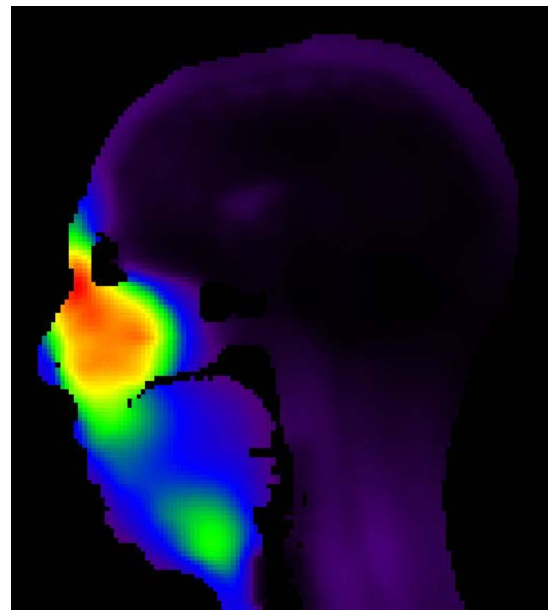
Muscle

- Electrical conductivity = 0.98 S/m
- Blood flow = 3 ml/(100 g.min) at rest
- Moderate conductivity and low blood perfusion (at rest) $\Rightarrow$ peak ΔT in the body



SAR

(peak 10 g SAR = 0.32 W/kg)



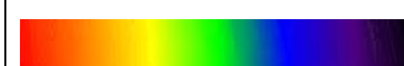
ΔT

(peak ΔT = 0.10 °C)

1 GHz plane-wave

5 W/m^2

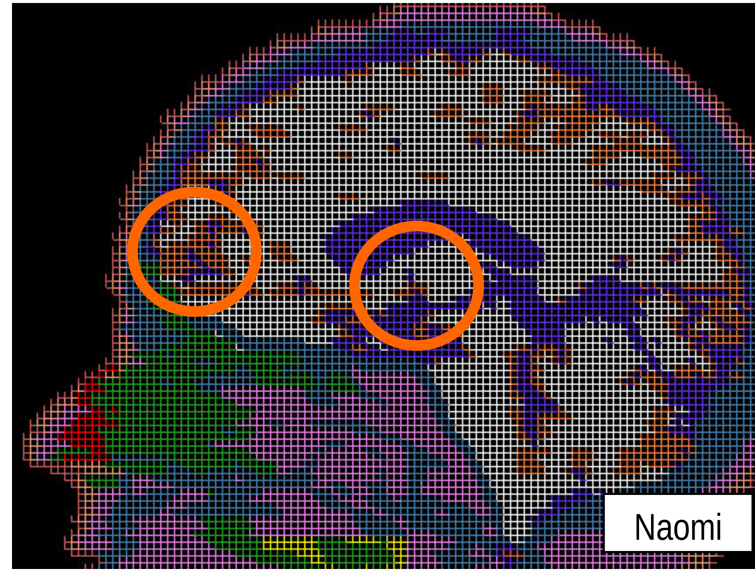
100% 50% 0%

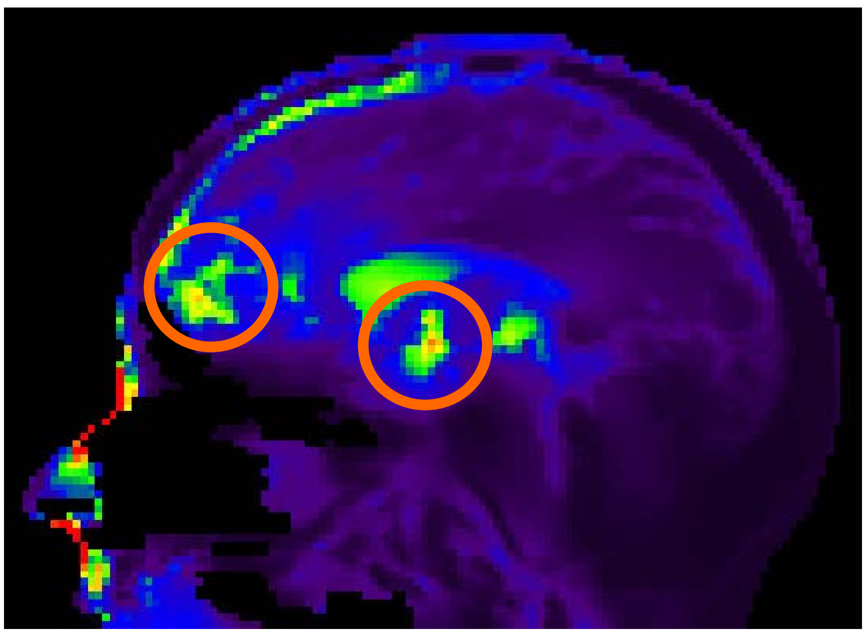


Grey Matter

- Electrical conductivity = 0.99 S/m
- Blood flow = 81 ml/(100 g.min)

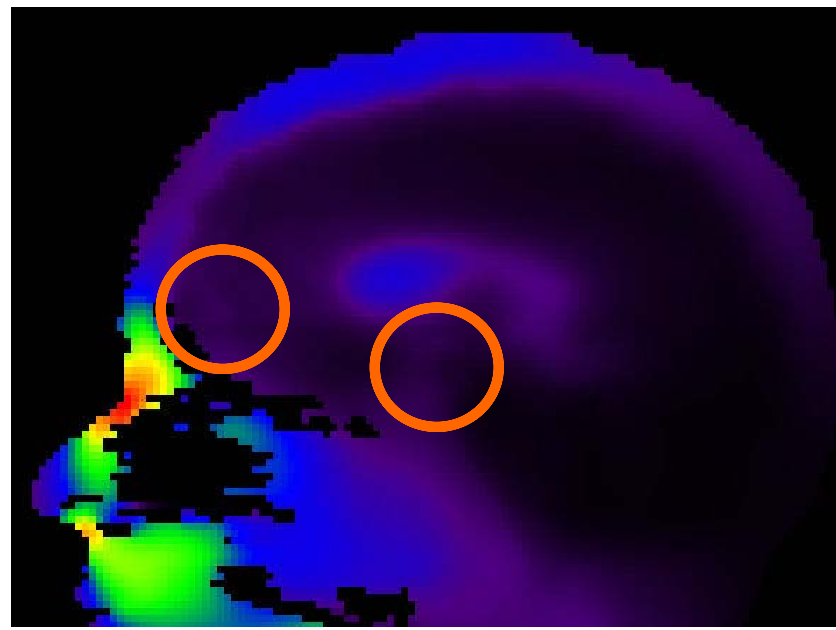
- High blood perfusion $\Rightarrow$ low ΔT





SAR

(peak 10 g SAR = 0.18 W/kg)



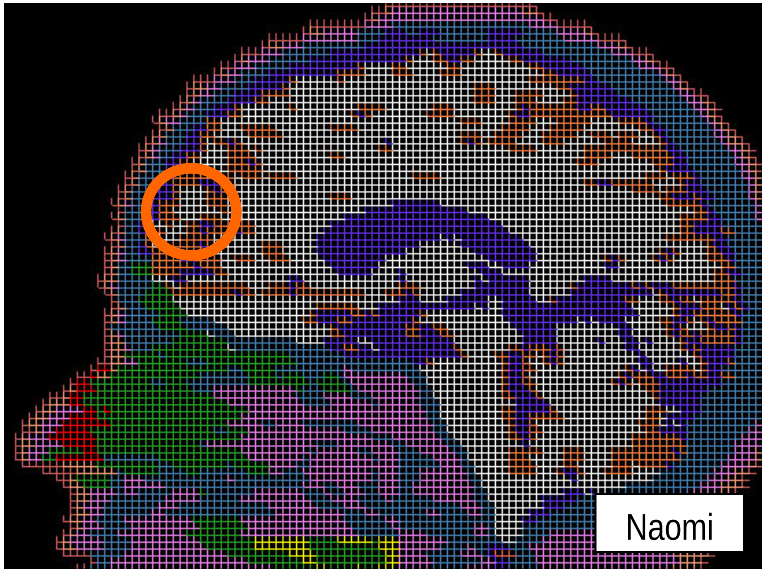
ΔT

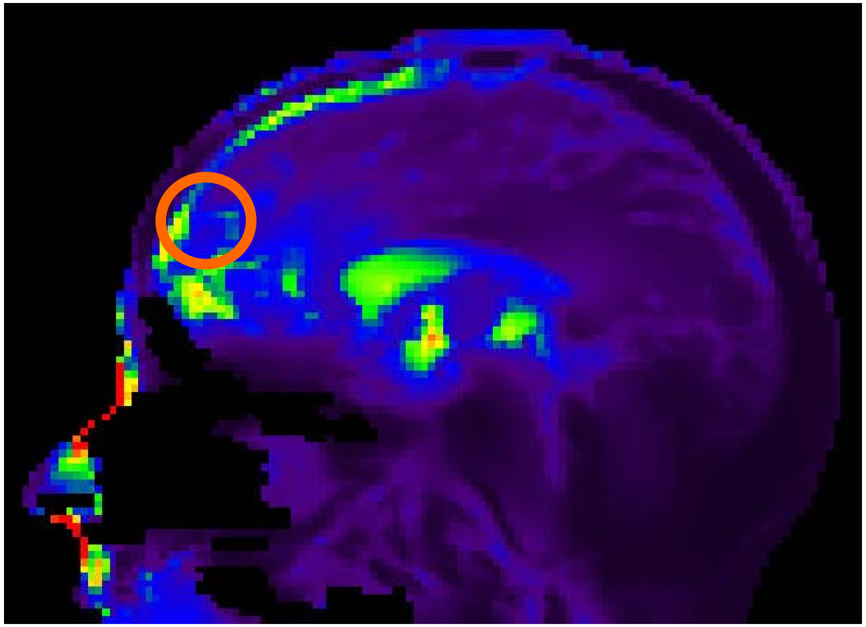
(peak ΔT = 0.02 °C)

White Matter

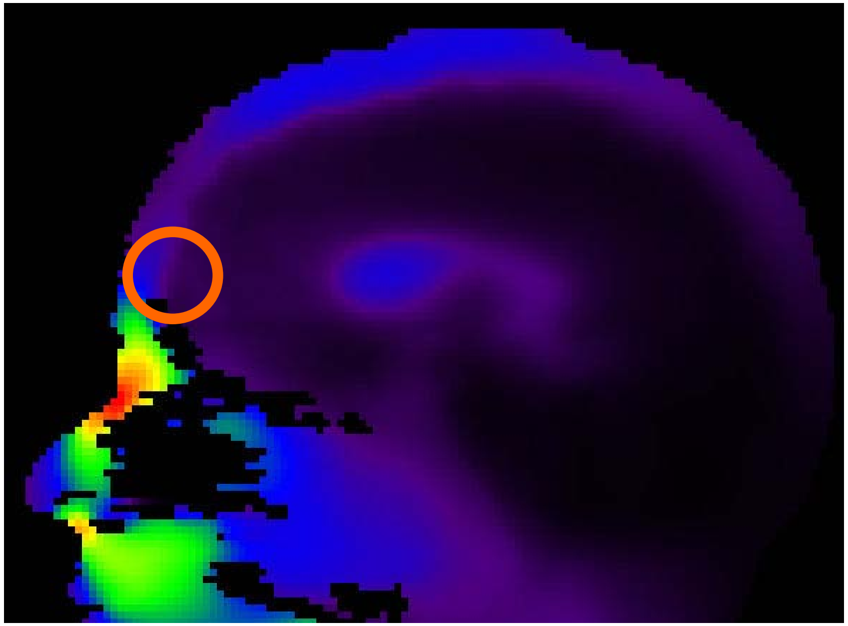
- Electrical conductivity = 0.62 S/m
- Blood flow = 20 ml/(100 g.min)

- Low conductivity and moderate perfusion
  $\Rightarrow$ low ΔT





SAR
(peak 10 g SAR = 0.16 W/kg)

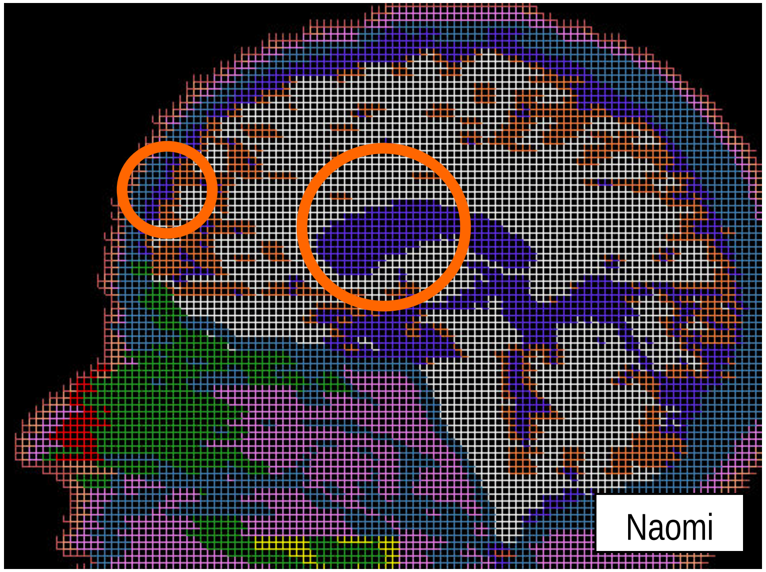


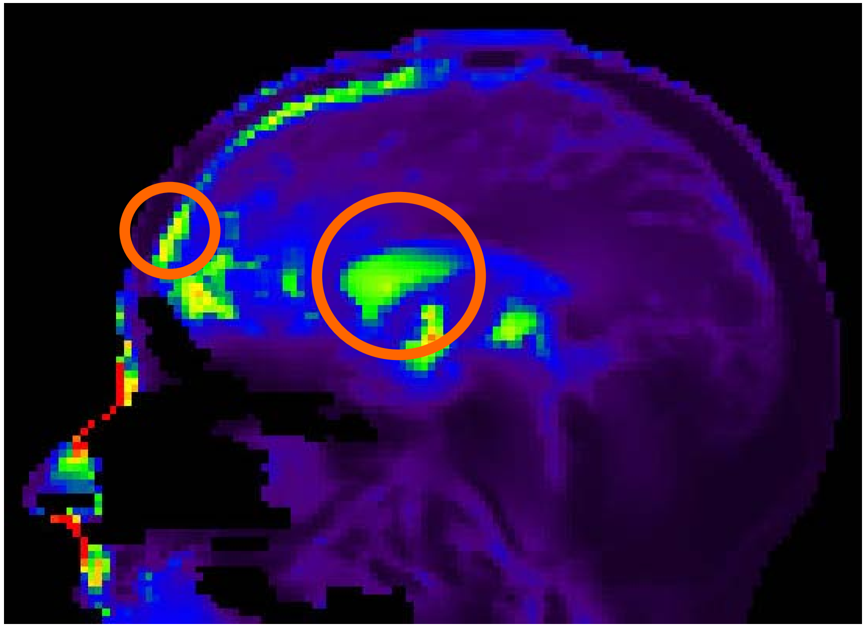
ΔT
(peak ΔT = 0.03 °C)

CSF

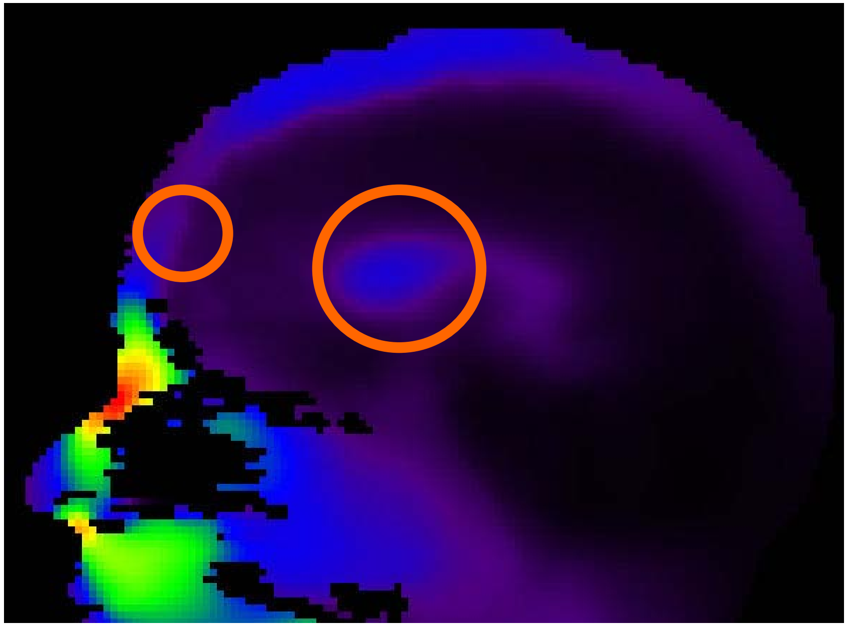
- Electrical conductivity = 2.46 S/m
- Blood flow = 0

- High conductivity and negligible perfusion





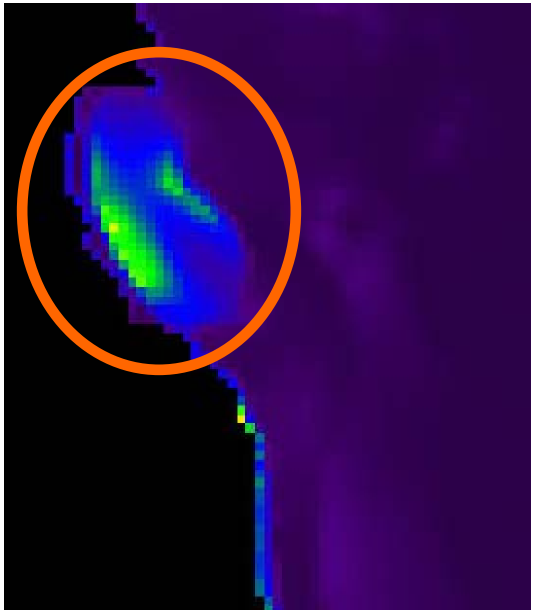
SAR
(peak 10 g SAR = 0.18 W/kg)



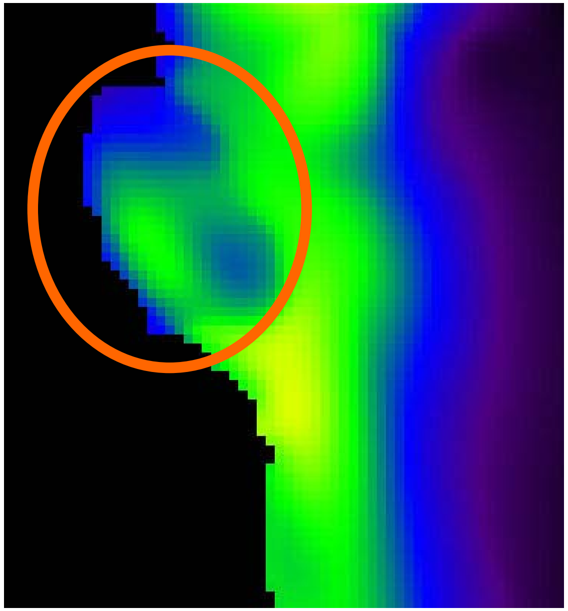
ΔT
(peak ΔT = 0.03 °C)

Testes

- Electrical conductivity = 1.35 S/m
- Blood flow = 23 ml/(100 g.min)   (Wax & Peterson (1967) for dog testes)

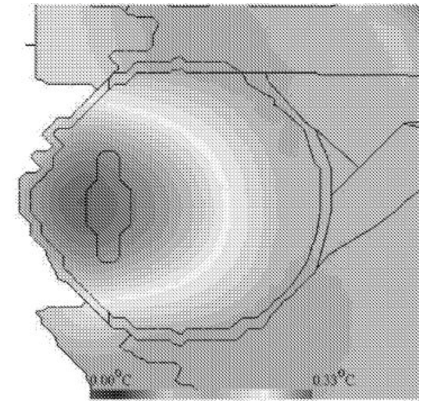


SAR
(peak 10 g SAR = 0.15 W/kg)



ΔT
(peak ΔT = 0.02 °C)

Eyes

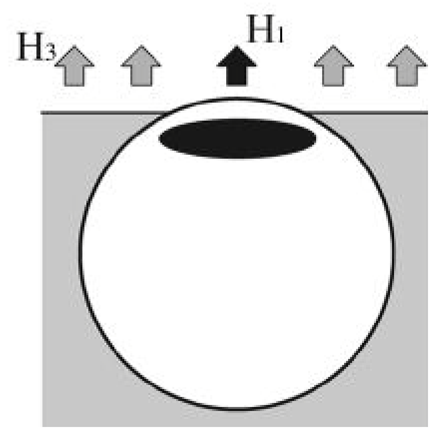


- **High resolution models** have been developed

  e.g. Wainwright 2007, Hirata et al. 2007 & 2008, & Schmid et al. 2007

- Blood Perfusion
  - Negligible for cornea, lens, and vitreous and aqueous humour
  - High on periphery (ciliary body, iris, and choroid)

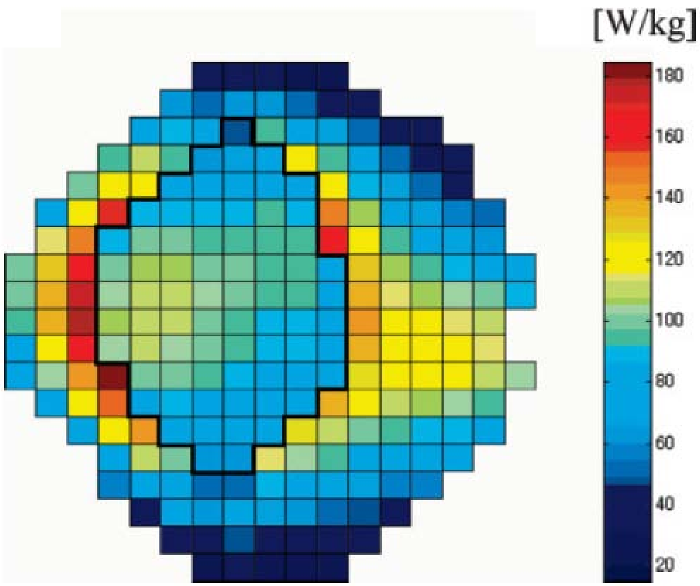
- **Heat convection**, *h*, different between skin & eye
  - From eye to air: 20-50 W/(m^2.°C)
  - From skin to air: 8-10 W/(m^2.°C)
  - Heat stress leads to higher tear evaporation and *h* increases leading to decrease in ΔT (De Santis & Feliziani 2008)



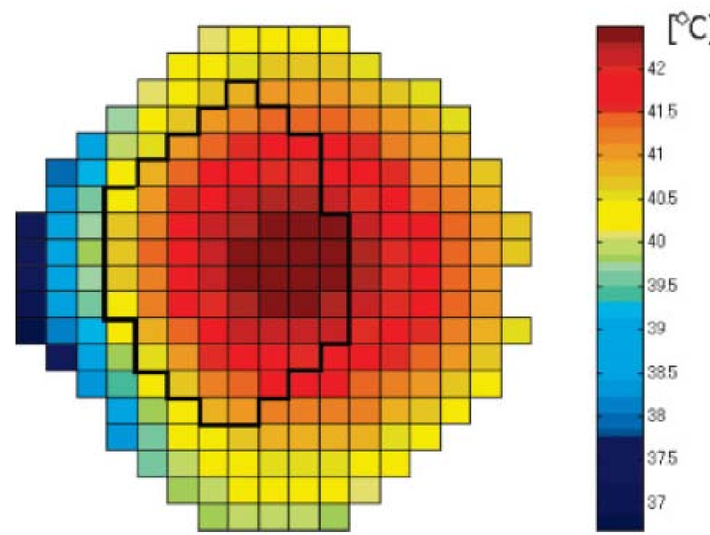
- SAR
  - ~ 0.35 °C for 2 W/kg (Hirata et al. 2005)
  - Highest average SAR at 2-3 GHz (Hirata et al. 2007)

Hirata et al. (2006)

- Rabbit Eyes Exposed to 2.45 GHz Microwave Energy
- Blood perfusion increased as temperature increased
- Results suggest highest ΔT in the lens and vitreous humour



SAR



Temperature

Cross section of rabbit eye under 2.45 GHz exposure at 3,000 W/m^2

Acknowledgements

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