# Ocular studies of EMF exposure at the MMW

## : Numerical dosimetry and mathematical model to estimate cornea damage

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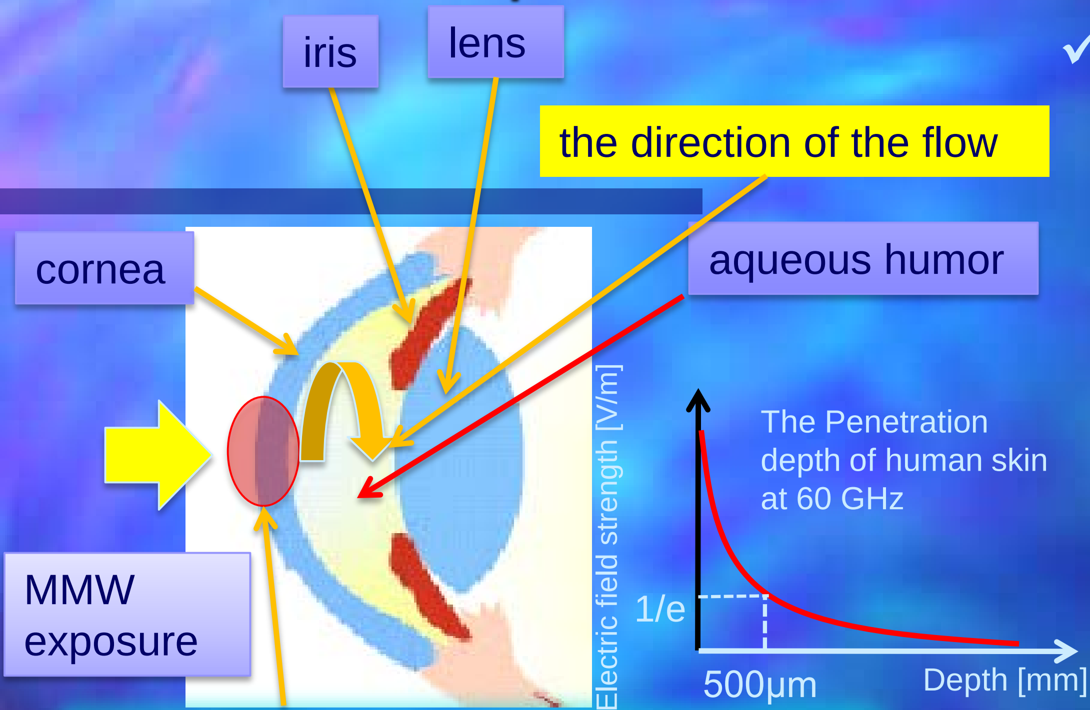
2018/06/24
Pre Conference Workshop
EMF exposure from 5G equipment

# purpose

- To evaluate power absorption and temperature elevation for ocular tissue (especially cornea) due to MMW exposure, numerical dosimetory and heat transport analysis were performed.
- In addition, to predict cornea epithelium damage, mathematical model based on CEM43ºC criteria was examined for 28, 40, 75, and 95GHz exposure, these include 5G frequency condition.

# Heat transport mechanism for MMW exposure




- ✓ The power absorption and the temperature elevation is highly localized within several hundred μm depth from the surface of the cornea.

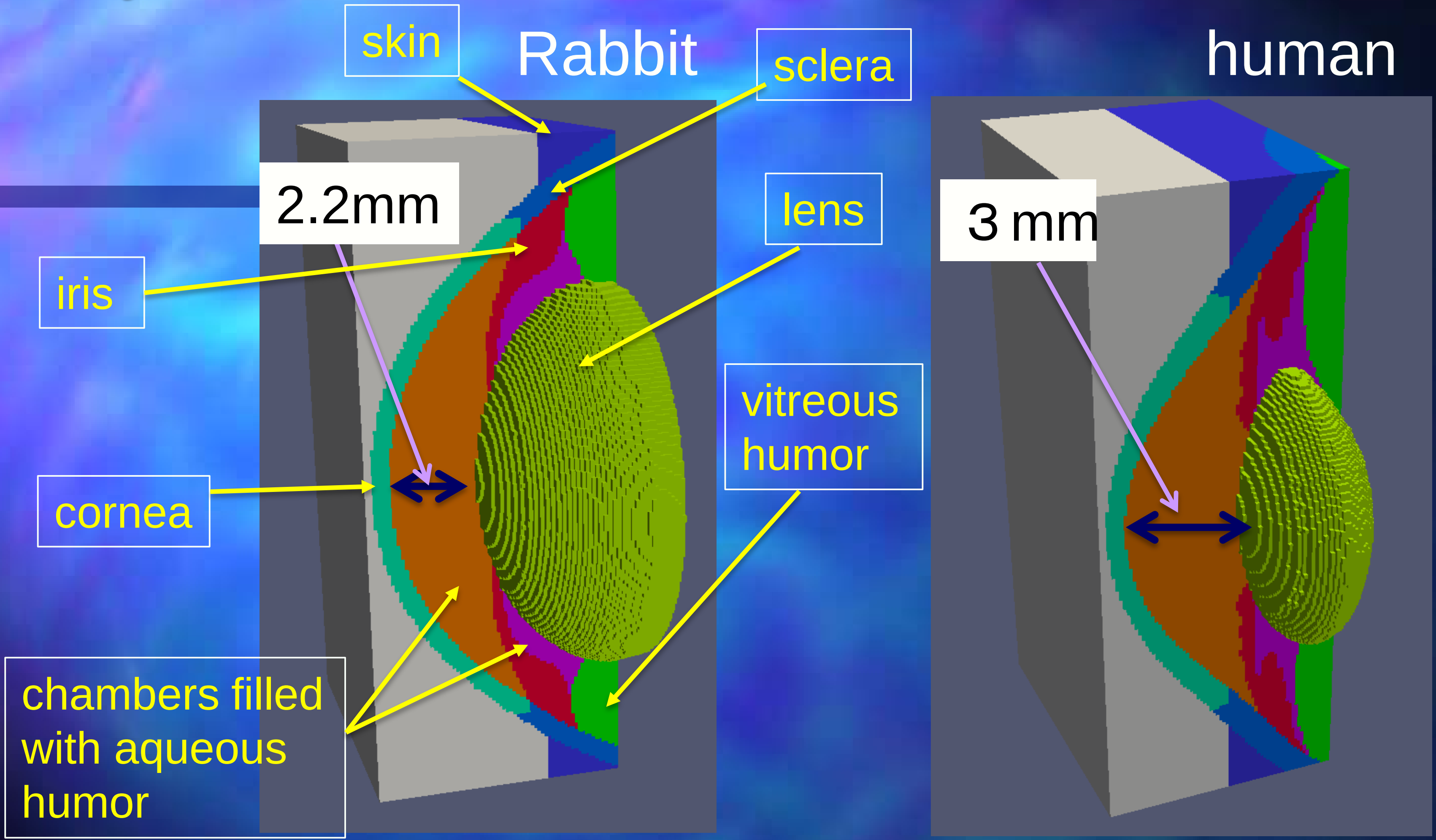
- ✓ Heat transport become complex in anterior chamber because of the existence of the aqueous humor.

Energy absorption is occurred .

heating transportation pattern: conduction / convection

✓ Temperature elevation of cornea surface is nonlinear to the input level of incident power density (PD).

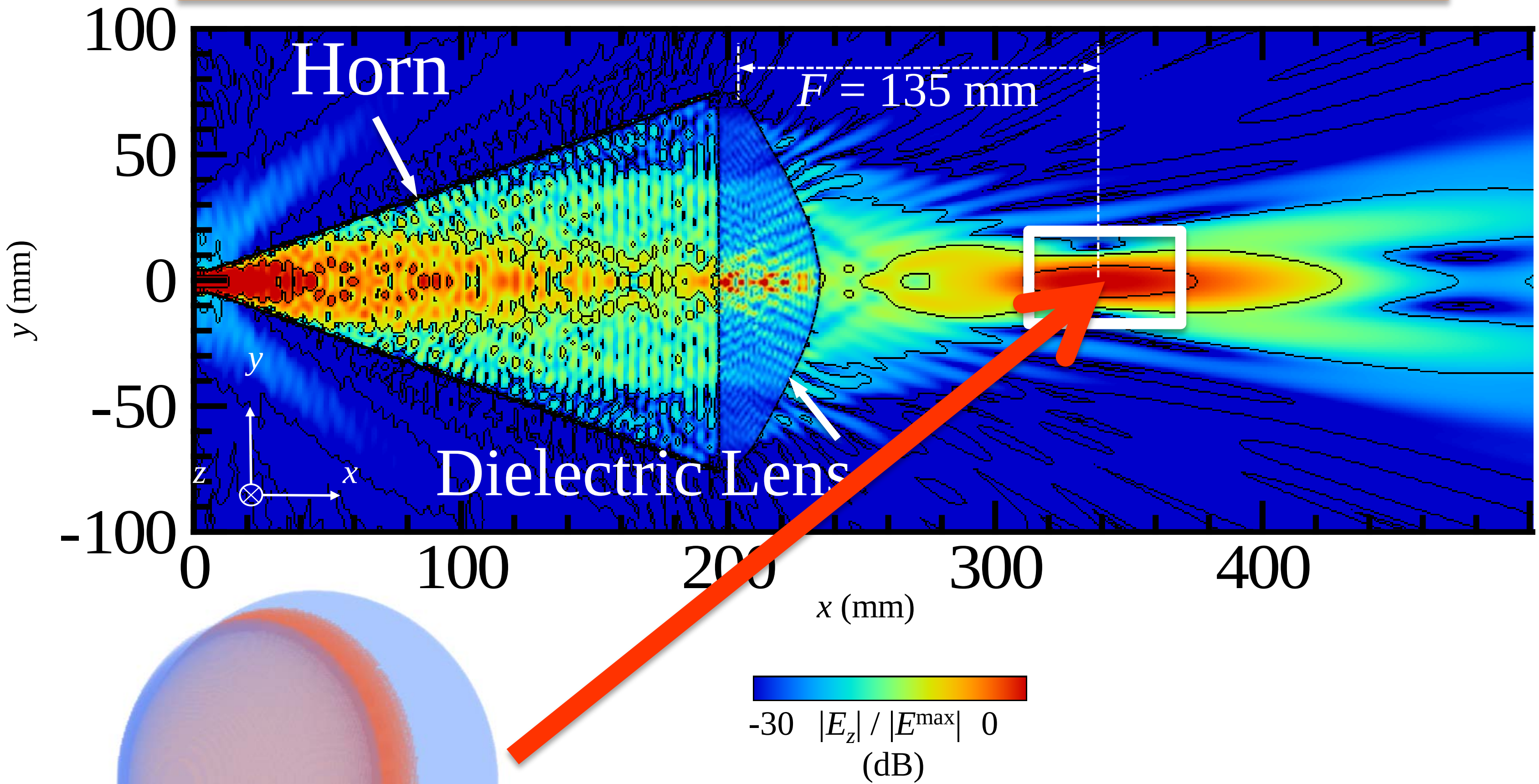
# Eye models of rabbit and human

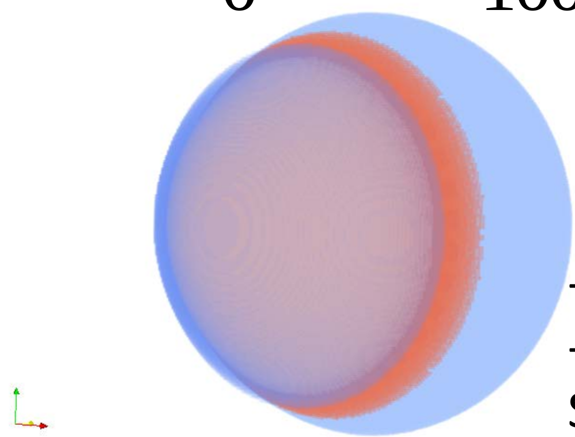



- ✓ These models are anatomically reviewed.
- ✓ Prepared 12.5, 25, and 50μm mesh sizes .
- ✓ Consists of 7 tissues, cornea, aqueous humor, iris, lens, vitreous humor, sclera, and skin.

# Simulation setup for EMF analysis

FDTD method was used to obtain induced EMF in the eye ball.



Eye ball

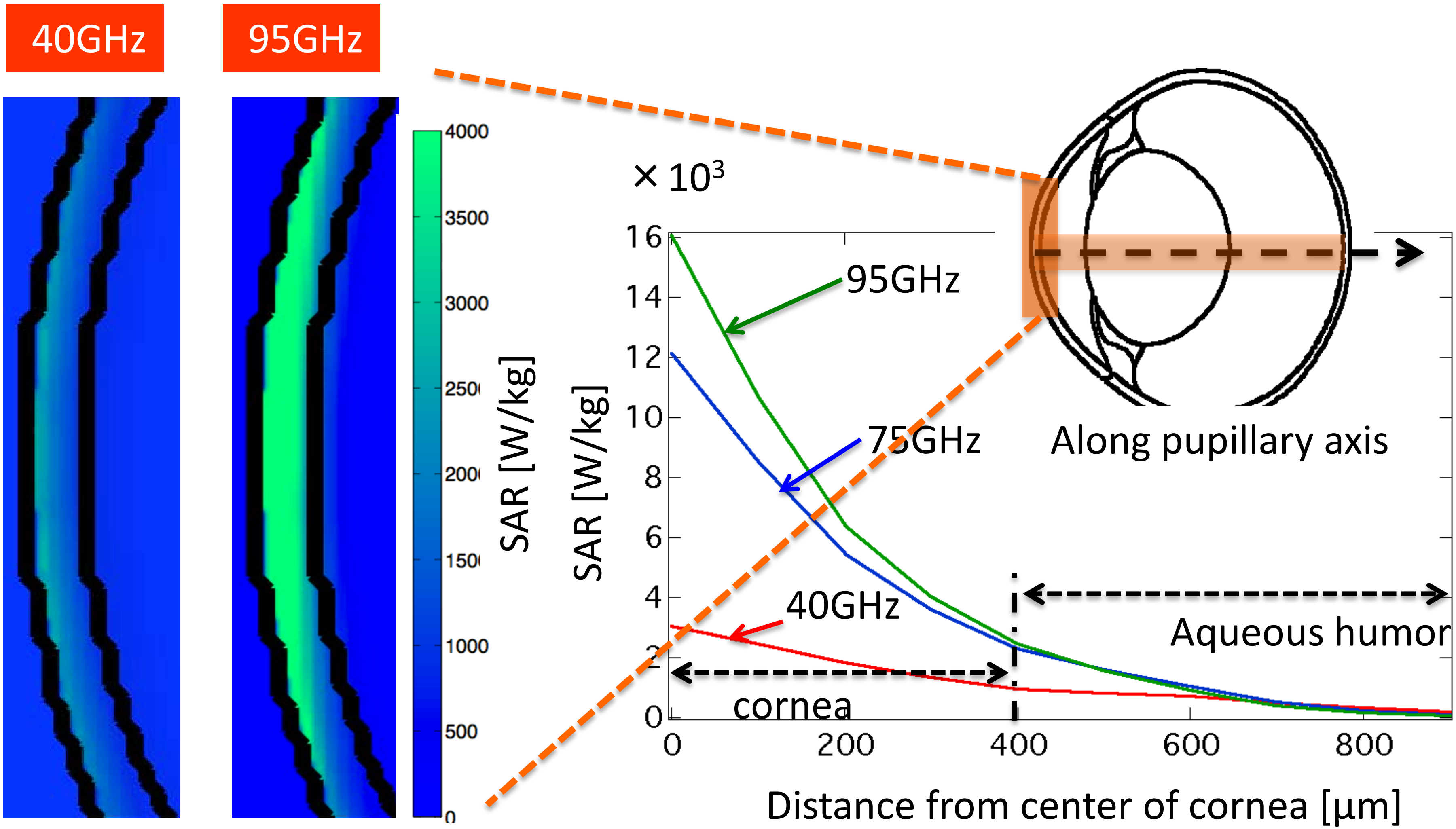
-The eyeball is placed at the focal point of lens antenna.

-Scattered field FDTD method is used to obtain induced SAR within eye

FDTD : Finite Difference Time Domain method

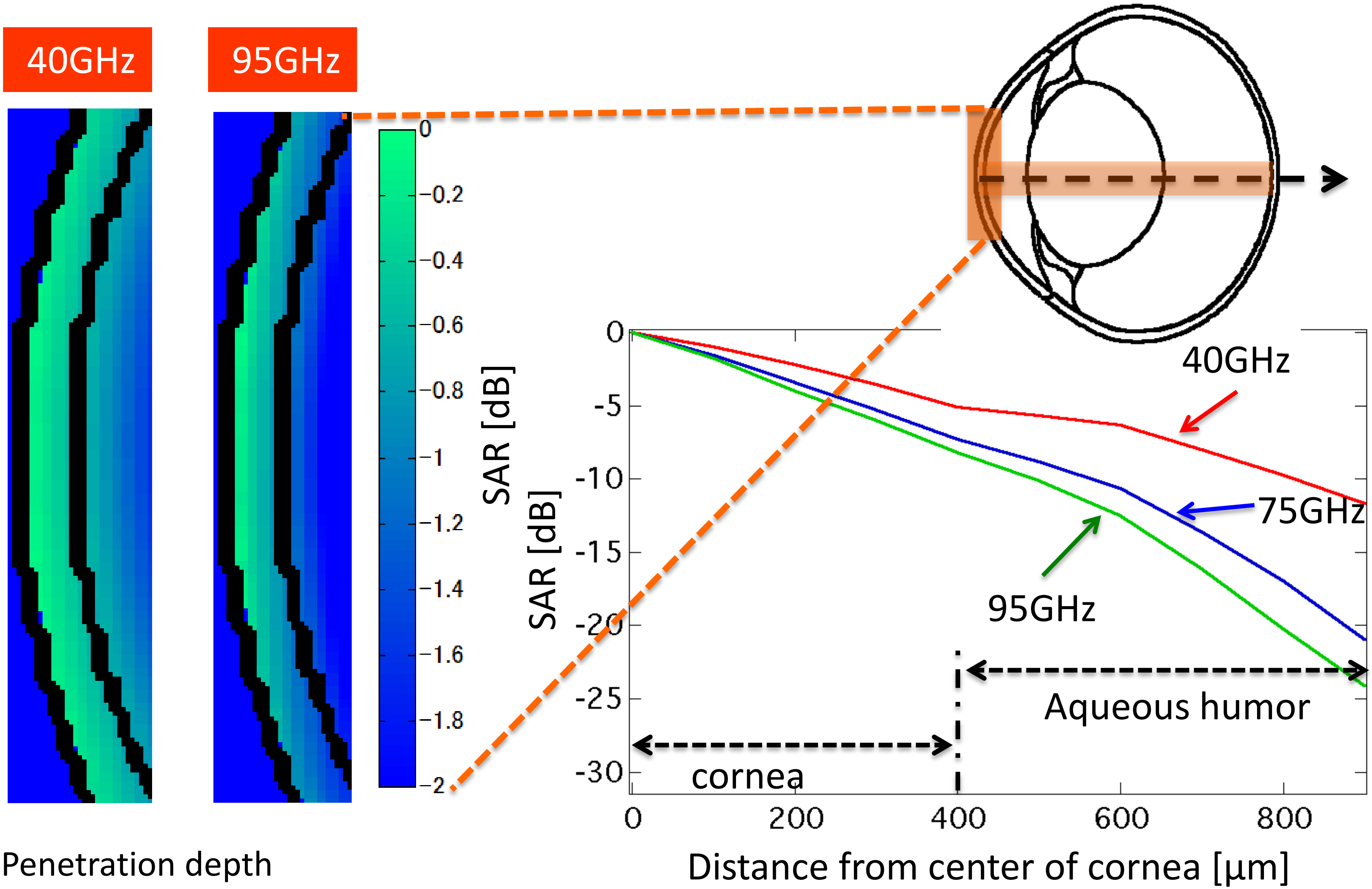
# SAR distribution for each frequency

※Power density 100mW/cm$^2$




-SAR value becomes large according to the increase of frequency.

# Comparison of penetration depth




Penetration depth
40GHz:500μm, 75GHz:350μm, 95GHz:250μm

# Equations for heat transport simulation

- Non-compressive fluid
- Boussinesq approximation
- SMAC (Simplified marker and cell) method is used

**Physical constants**

- density: ρ [kg/m$^3$]
- coefficient of kinematic viscosity: ν
- specific heat : Cp [J/kg・K]
- heat conduction coefficient : K [W/m・K]
- metabolic heat : $A_0$ [W/m$^3$]
- Coefficient of blood flow : B [W/m$^3$・K]
- heat source : Q [W/m$^3$]
- gravity :**g** [m/s$^2$]

**Continuity equation**

$$\nabla \cdot \vec{V} = 0$$

**Navier-storkes equation**

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla)\vec{V} = -\frac{1}{\rho}\nabla p + \nu \Delta \vec{V} + \vec{g}$$

**Biological heat transpot equation**

$$\rho C_p\left(\frac{\partial T}{\partial t} + (\vec{V} \cdot \nabla)T\right) = \nabla \cdot (K \nabla T) + A_0 - B(T - T_{blood}) + Q$$

$$Q = \rho SAR$$

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

**Calculation of pressure**

$$\Delta p' = \frac{\rho}{dt} \nabla \vec{V}^*$$

Convective energy transport term

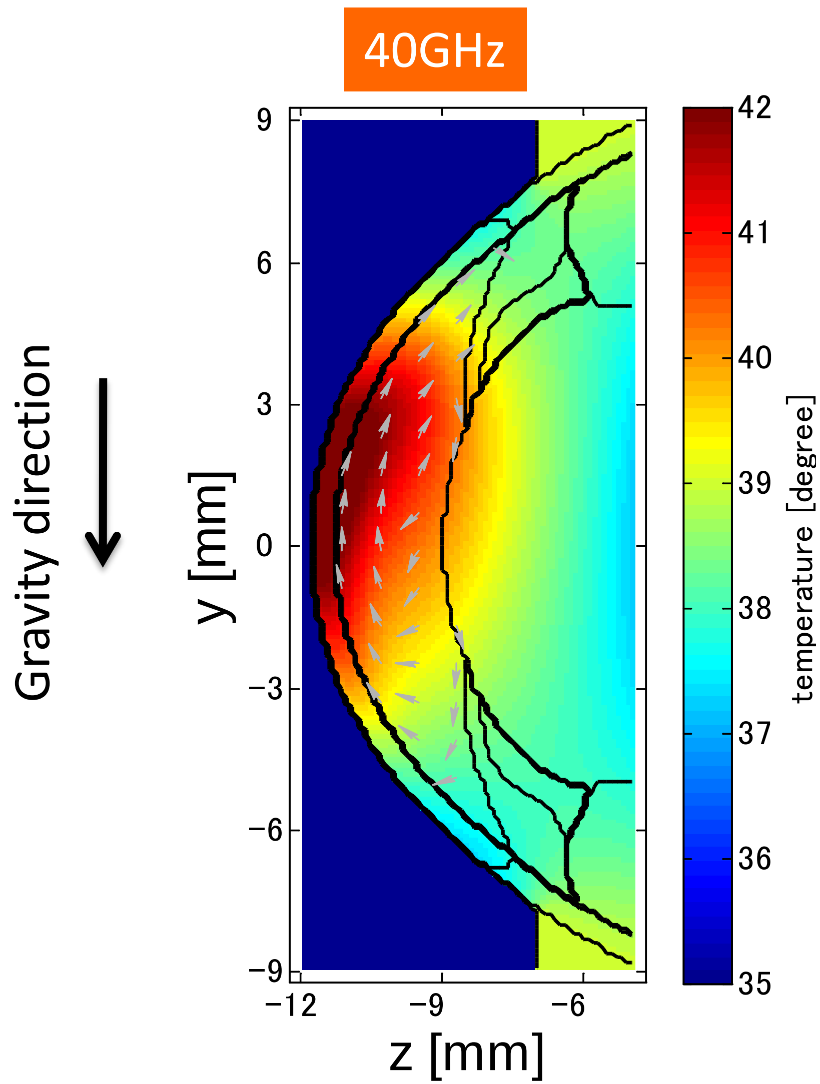
**Variables**

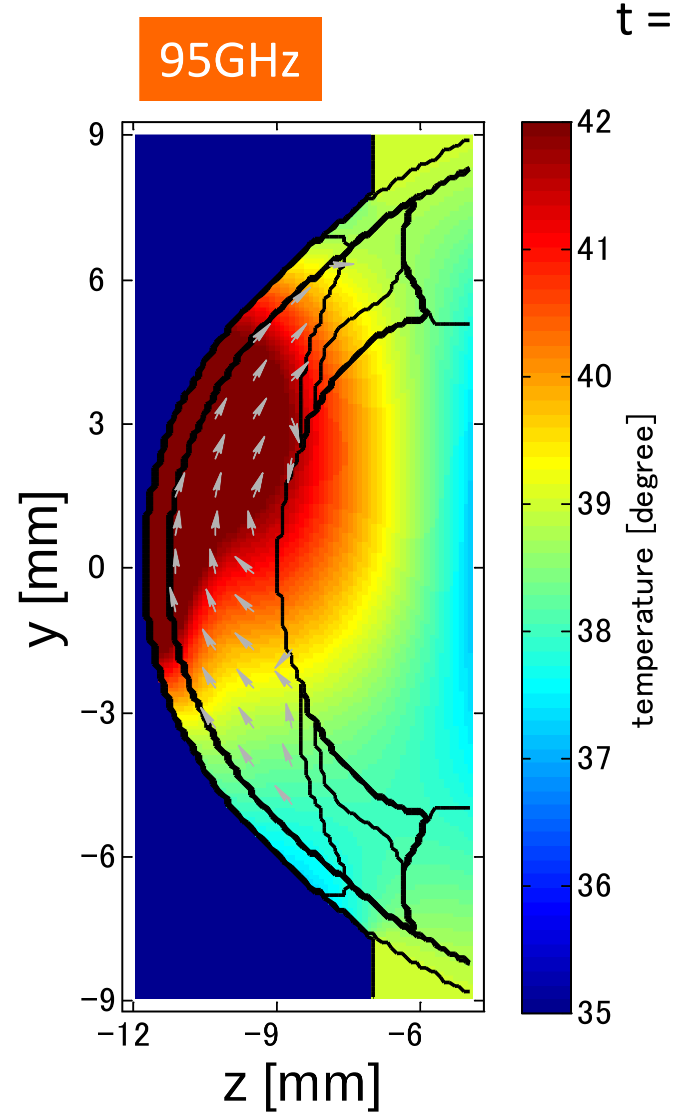
- velocity :**V**[m/s]
- temperature:T[℃]
- pressure:p[kg/m$^2$]

# Dependence of T and V on the frequency

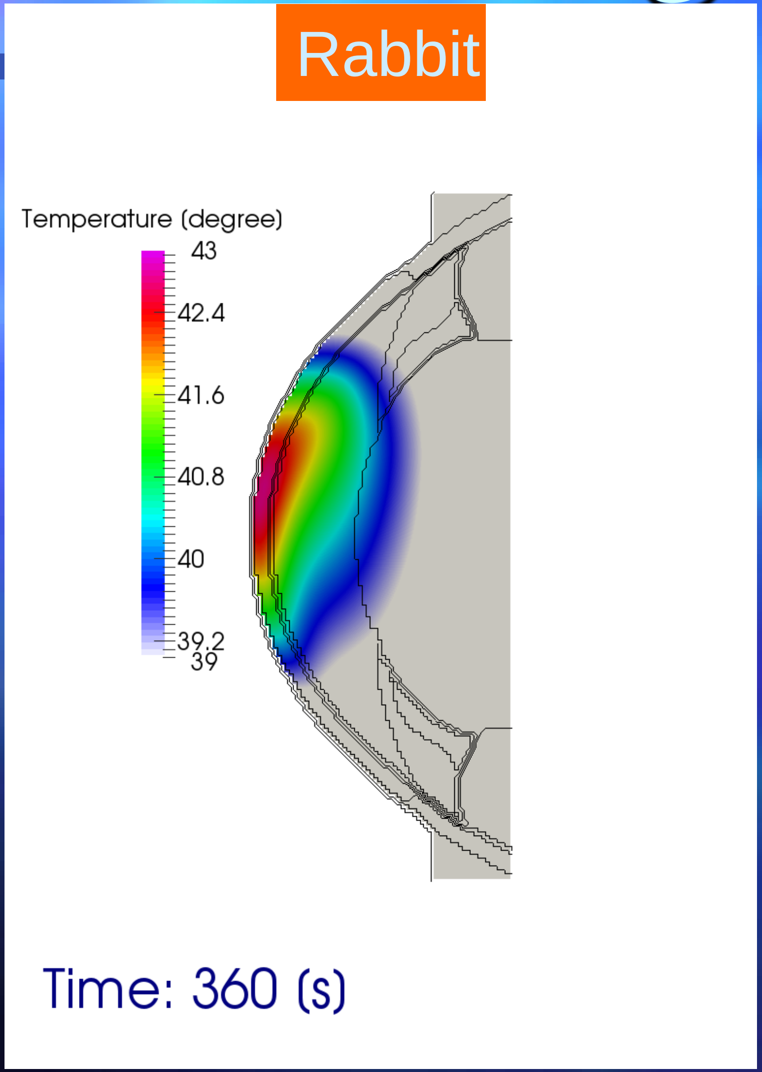
200mW/cm$^2$ 40GHz, 95GHz

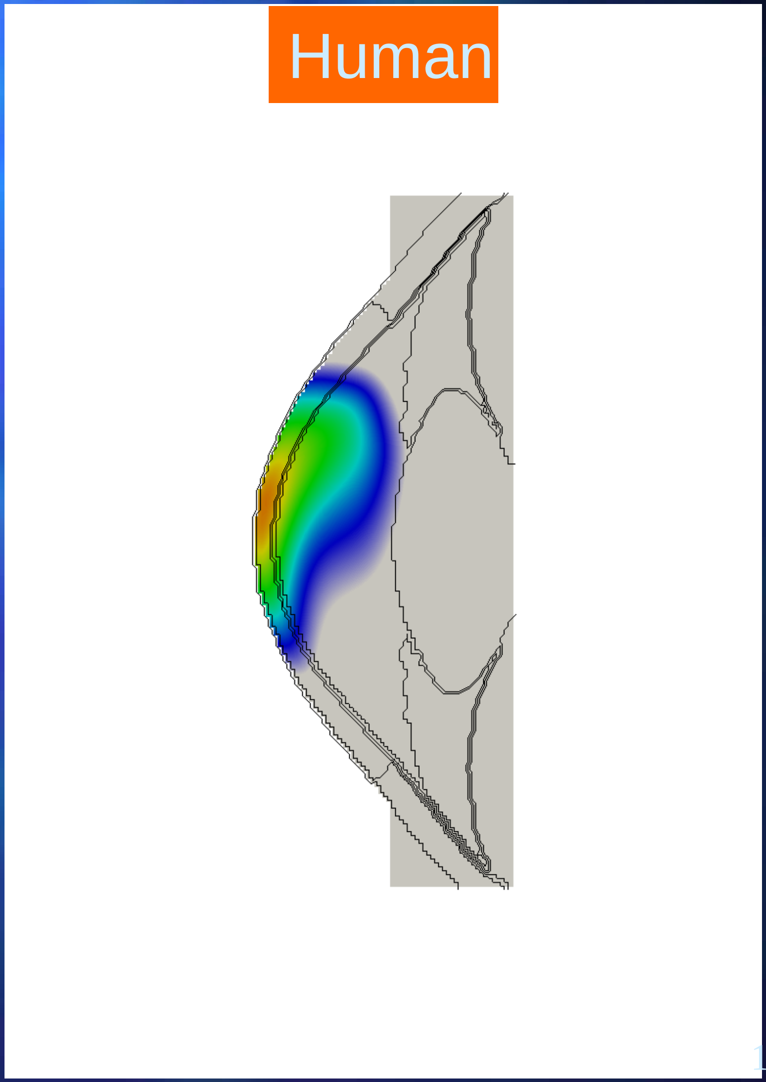
t = 360s



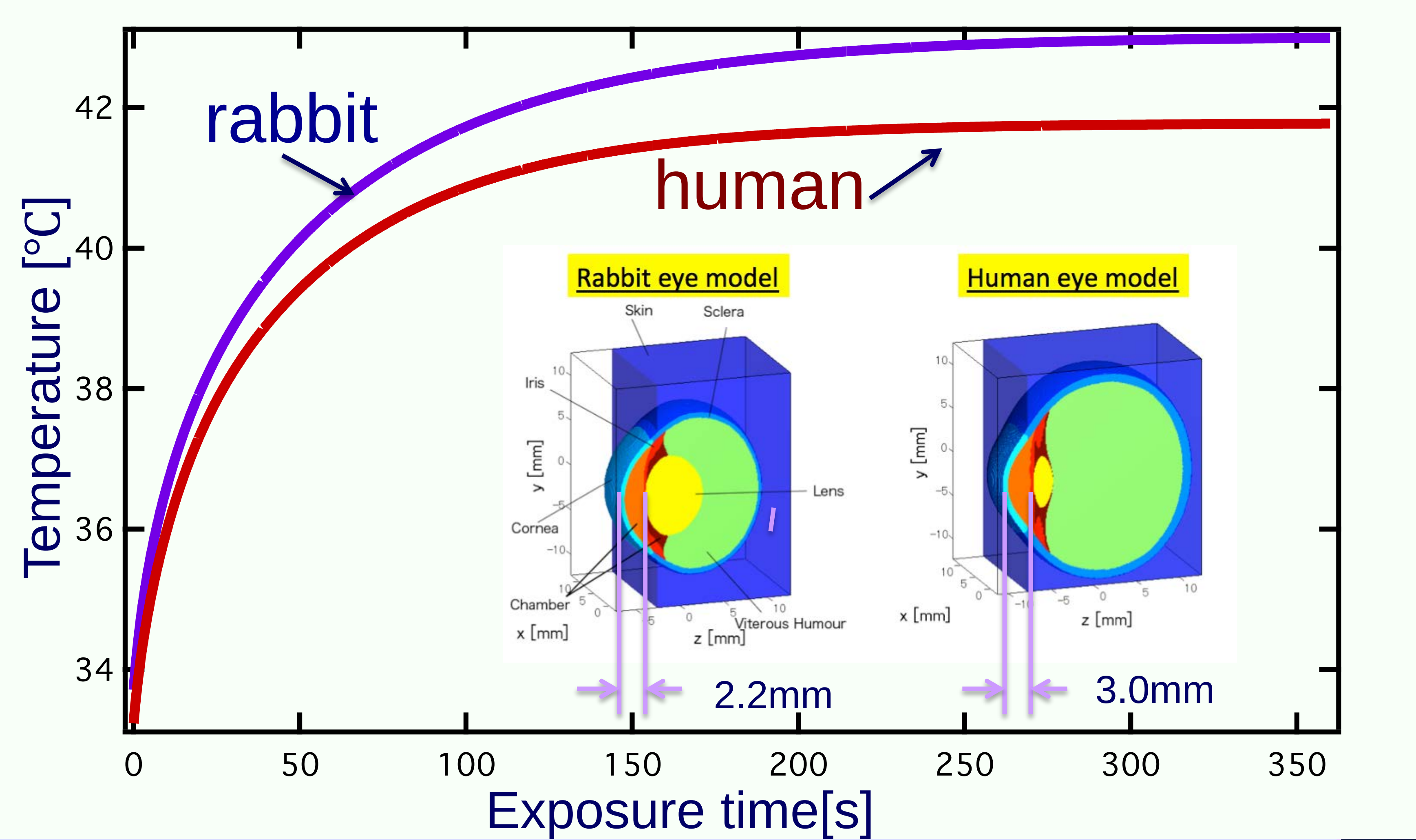



# Comparison of temperature distribution between rabbit and human 40GHz@200mW/cm$^2$



# Comparison of time course temperature elevation between rabbit and human(40GHz@200mW/cm$^2$ )




Human eye is superior in the heat transport ability, because of its deeper anterior chamber depth.

# Quantification of thermal dose

- The method to determine the thermal dose has been proposed for cancer therapy from 1984.[1-3]
  - This method is termed “thermal isoeffective dose”
  - Recently this method is  considered to apply to estimating threshold caused by thermal effect of MRI equipment.[4]
- The time–temperature data are converted to an equivalent number of minutes at 43ºC temperature exposure
  - 43ºC is the near the break point  for CHO and several other cell lines.


[1]Sapareto SA, Dewey WC. Thermal dose determination in cancer therapy. Int J Radiat Oncol Biol Phys 1984; 10: 787–800.

[2]Dewhirst MW, Viglianti BL, Lora-Michiels M, Hanson M, Hoopes PJ. Basic principles of thermal dosimetry and thermal thresholds for tissue damage from hyperthermia. Int J Hyperthermia. 2003; 19:267–294.

[3] Yarmolenko PS, Moon EJ, Landon C, Manzoor A, Hochman DW, Viglianti BL, Dewhirst MW, "Thresholds for thermal damage to normal tissues: an update", Int J Hyperthermia. 2011;27(4):320-43.

[4] van Rhoon GC1, Samaras T, Yarmolenko PS, Dewhirst MW, Neufeld E, Kuster N, "CEM43°C thermal dose thresholds: a potential guide for magnetic resonance radiofrequency exposure levels?", Eur Radiol. 2013 Aug;23(8):2215-27

# CEM43ºC criteria

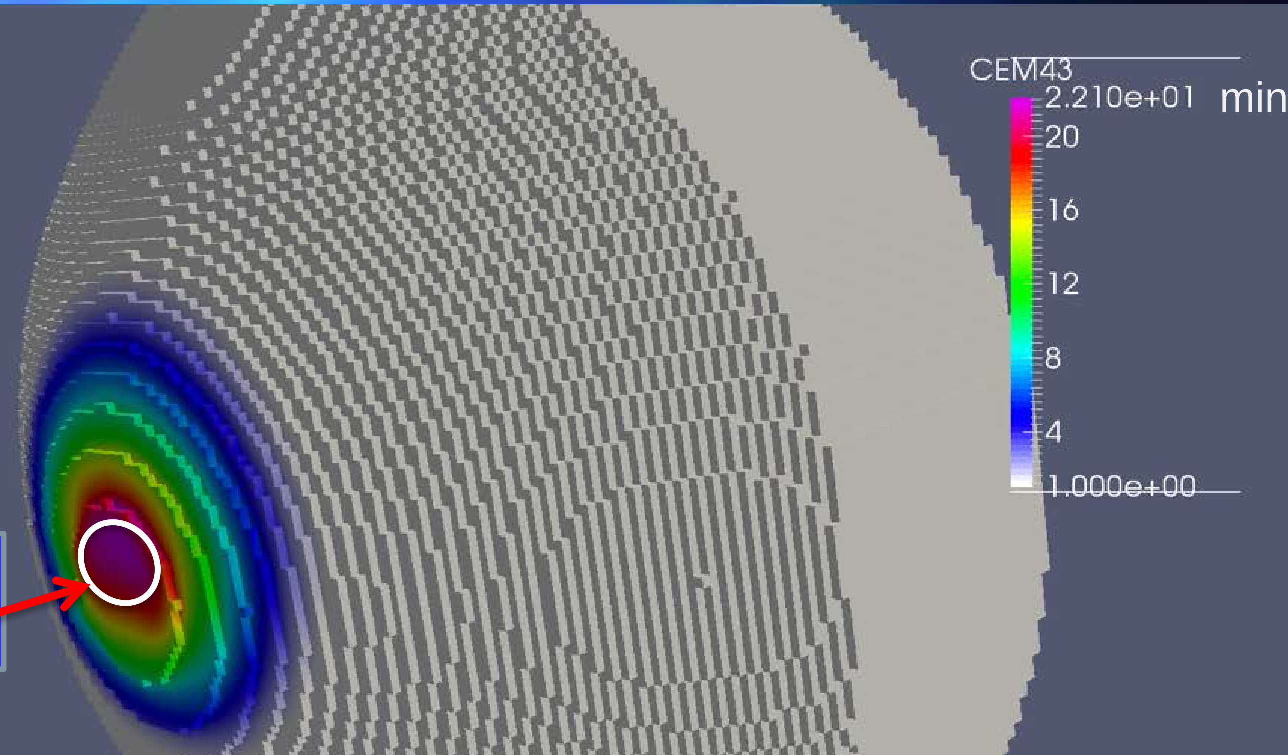
- Index of thermal isoeffective dose originally defined as follows.

$$CEM\,43^{\circ}C = tR^{(43-T)}$$

  - CEM 43ºC:cumulative number of equivalent minutes at 43ºC
  - t: time interval (min)
  - T: average temperature during time interval t.
  - R: the number of minutes needed to compensate for a 1º temperature change either above or below the breakpoint.
- As for cornea, thermal exposure causes
  - 21< CEM43ºC < 40 min: Acute and minor damage
  - 41< CEM43ºC < 22000 min: Acute and significant damage
  - 22000 < CEM43ºC : Severe damage.

# CEM43ºC distribution at 6min (75GHz 150mW/cm²)

-CEM43ºC distribution on the cornea surface.
-Exposure condition is 75GHz, 150mW/cm².
-An example of 6min exposure.



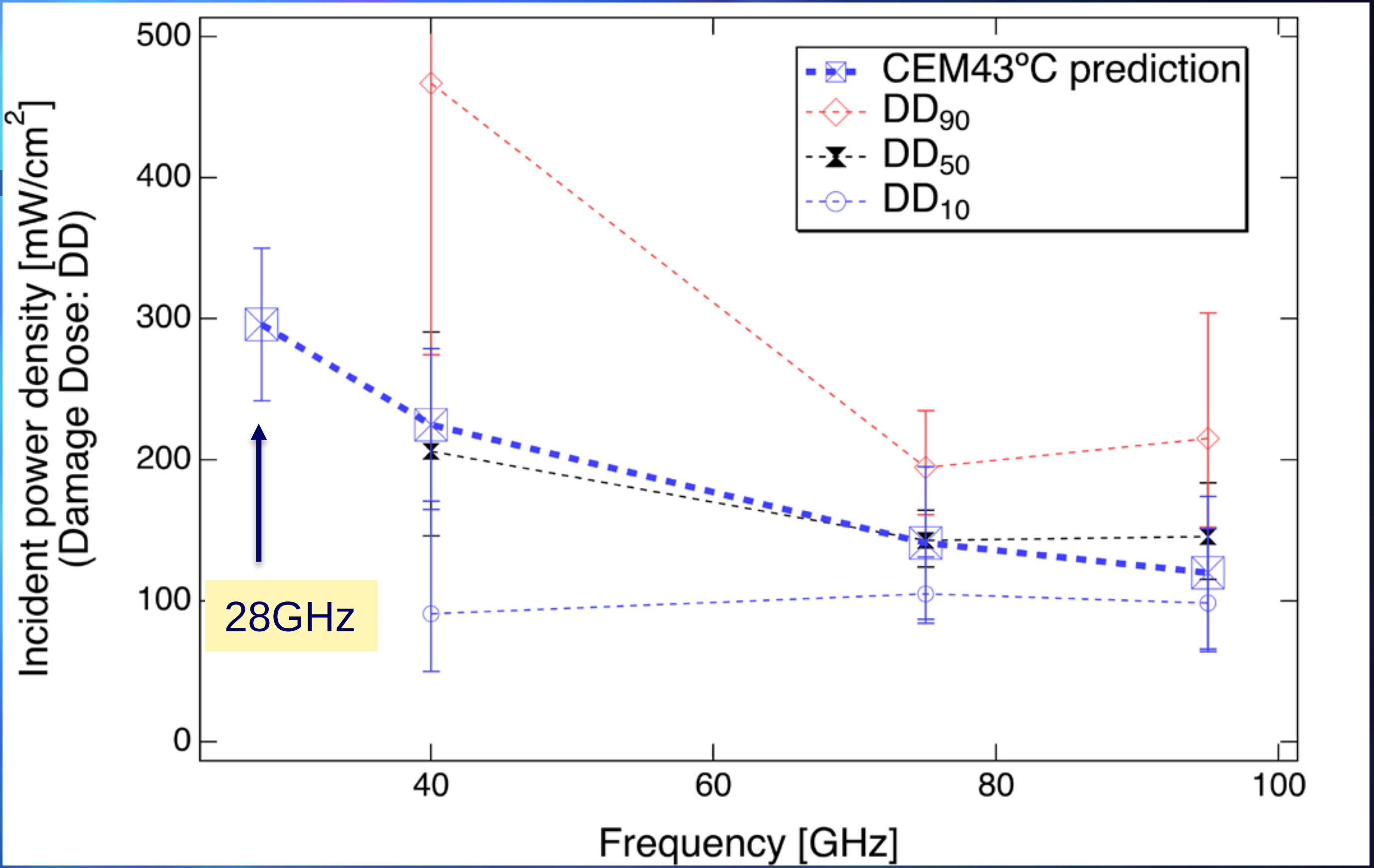

CEM43ºC is more than 21 minutes inside the circle

-21< CEM43ºC < 40 min: Acute and minor damage
-41< CEM43ºC < 22000 min: Acute and significant damage
-22000 < CEM43ºC : Severe damage.

Cornea damage is predicted inside the circle by CEM43ºC analysis.

# Prediction of PD threshold level for 6 min. exposure

| Freq. [Hz] | PD threshold [mW/cm²] |
|---|---|
| 28 | 296 |
| 40 | 225 |
| 75 | 141 |
| 95 | 120 |




- ✓ Predicted PD threshold level based on CEM43ºC criteria agree with $DD_{50}$ estimated by experiments.
- ✓ PD threshold level for 28GHz exposure will be lager value than that for high frequency.

# Summary

- Characteristics of temperature elevation distribution are different between different frequency, and between rabbit and human.
  - Results of rabbit indicate higher temperature elevation than that of human.
- Threshold level of power density become higher (relaxed) based on the CEM43ºC analysis, according to the decrease of frequency.

Thank you for your kind attention !

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# The multi-physics simulation system for ocular exposure to MMW

The system is consists of 3 part:

**Reconsttuction of incident EMF**

2D electromagnetic field due to lens antenna is measured

↓

**Method** : PWS ( **P**lane **W**ave **S**pectrum ) method

↓

3D incident electromagnetic field is reconstructed

**EMF analysis**

3D electromagnetic field + eye model

↓

**Method** :
3D scattered-field FDTD (**F**inite **D**ifference **T**ime **D**omain ) method
＋rabbit eye model

↓

induced electromagnetic field in the rabbit eye → SAR

**Heat Transport analysis**

SAR ( **S**pecific **A**bsorption **R**ate )

↓

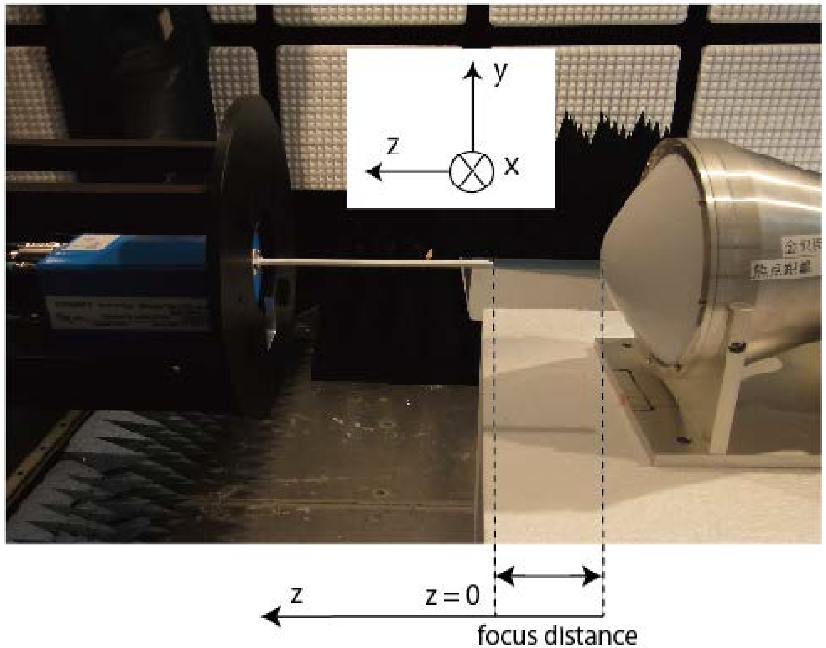
**Heat Transportation** — { **Heat Convection**, **Heat Conduction** }

**Method** : SMAC (Simplified marker and cell) method

➡ Temperature and flow velocity + ( pressure )

# The reconstruction of 3D EMF ( **E**lectro**M**agnetic **F**ield )

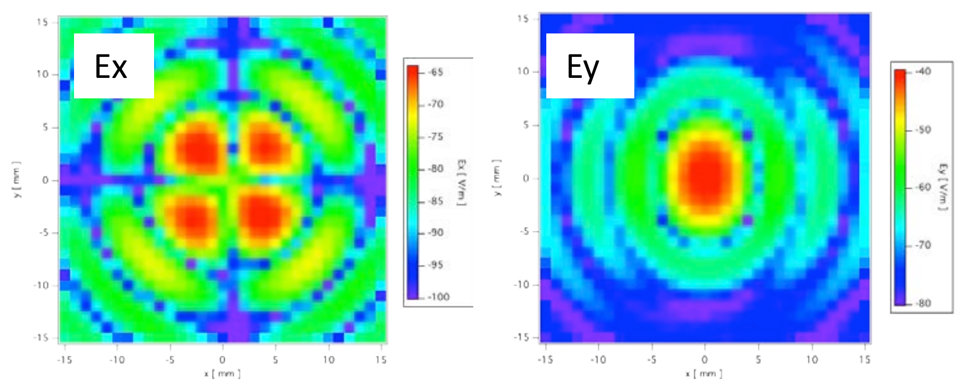
•2D EMF was measured against the lens antenna for the reconstruction of the incident field.[4]




The experimental condition

| | |
|---|---|
| Frequency | 75.4 [ GHz ] |
| The mesh size | 1.0 [ mm ] |
| Measurement area ( focus ) | 3 × 3 [ $cm^2$ ] |
| Focus distance | 150 [ mm ] |

EF measured at the focus (x-y dimension)




•The waveguide is used for the measurement.

•The electric field (Ex and Ey distribution ) was measured at the focal point with the lens antenna fixed by the z<0 side.

# The Method of reconstruction of 3D electric field : PWS

- Measured 2D electric field is converted by Fourier transform under the assumption.
  - -The incident wave is plane wave to obtain the electric field in the wave number space.
- 3D electric field is reconstructed by the inverse Fourier transform.

**Fourier transform**

$$\tilde{E}x(k_x,k_y) = \iint Ex(x,y,0)e^{j(k_x x+k_y y)}dxdy$$

$$\tilde{E}y(k_x,k_y) = \iint Ey(x,y,0)e^{j(k_x x+k_y y)}dxdy$$

The condition of calculation for PWS

| | |
|---|---|
| The number of meshes | 500 × 500 × 500 [ cells ] |
| Size of mesh | 50 [ μm ] |
| The reconstructed area | 25 × 25 × 25 [ $mm^3$ ] |

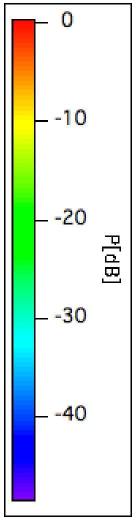
**inverse Fourier transformation**

$$Ex(x,y,z) = \frac{1}{(2\pi)}\iint \tilde{E}x(k_x,k_y)e^{-j(k_x x+k_y y+k_{0z}z)}dk_x dk_y$$

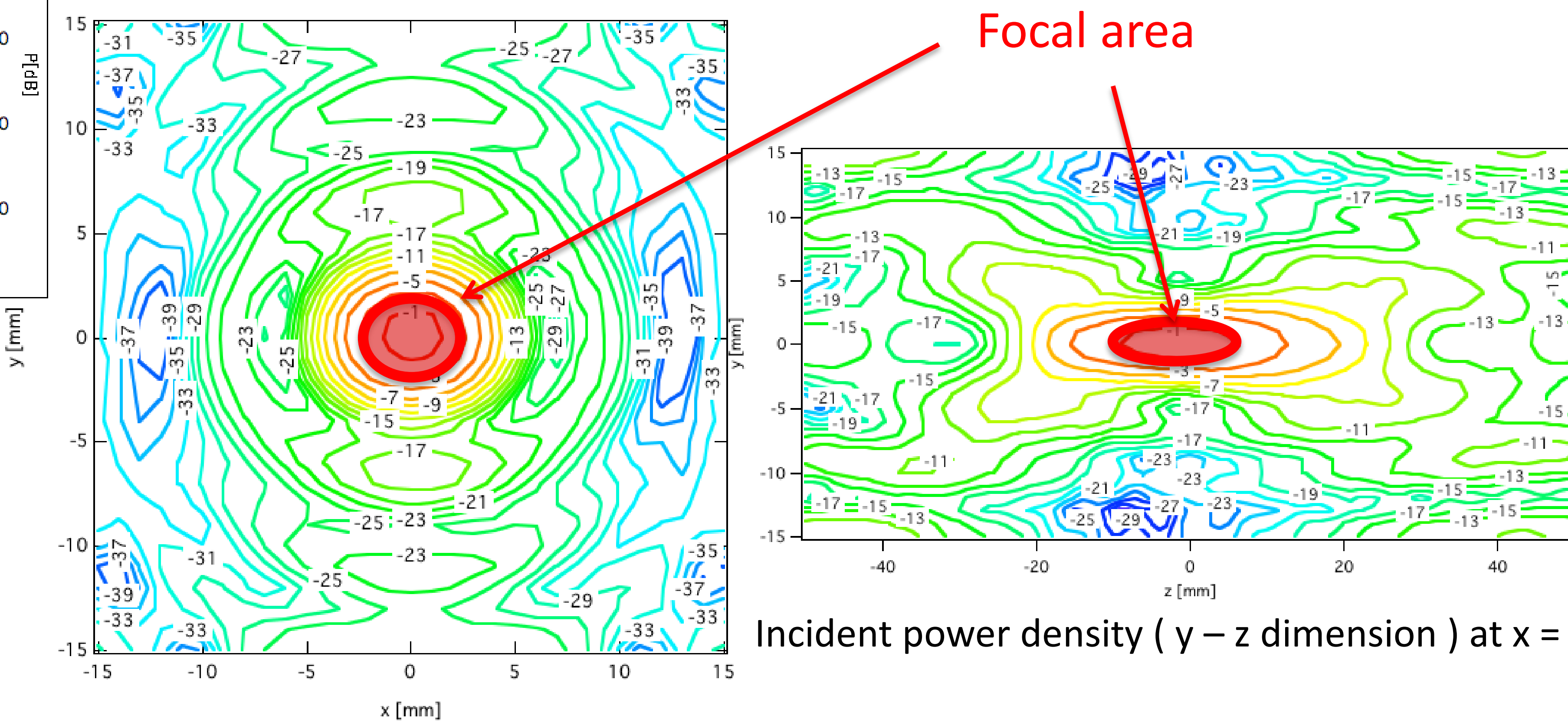
$$Ey(x,y,z) = \frac{1}{(2\pi)}\iint \tilde{E}y(k_x,k_y)e^{-j(k_x x+k_y y+k_{0z}z)}dk_x dk_y$$

$$Ez(x,y,z) = \frac{1}{(2\pi)}\iint \left\{\left(\hat{x}-\frac{k_x}{k_{0z}}\right)\tilde{E} + \left(\hat{y}-\frac{k_y}{k_{z0}}\right)\tilde{E}y\right\}e^{-j(k_x x+k_y y+k_{0z}z)}dk_x dk_y$$

However $k_{z0} = \sqrt{k_0^2 - k_x^2 - k_y^2}$




# The result of reconstructed 3D electric field




Incident power density ( y – z dimension ) at x = 0

Incident power density ( x - y dimension ) at the focus

- We can reconstruct realistic incident electric field.
- It is normalized by the maximum value of electric field.
- It is found that lens antenna generates highly localized electric field.