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Advanced Physical Phantoms for Evaluation of Interactions between the Human Body and Electromagnetic Waves

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Abstract It is essential to evaluate interactions between the human body and electromagnetic waves radiated from antennas for mobile terminals or other wireless devices to be used in the vicinity of the human body. The "interactions" mean two different ways: an influence of the human body on the performance of the antenna or wireless device as well as an influence of electromagnetic waves on the human body. Such interactions are estimated by numerical simulation and/or experimental evaluation.

Today, computational simulation with numerical human-body phantoms or models is a very powerful tool and many commercial softwares are available. However, results of numerical simulation should be validated with other techniques such as an experiment with physical phantoms.

As conventional physical phantoms, tissue-equivalent liquid, gel, semi-hard (semi-solid) or solid phantoms have usually been employed according to the purposes or situations. In our laboratory, we have studied and developed different types of semi-hard phantoms for many years.

This presentation introduces some examples of advanced physical phantoms including (a) inhomogeneous phantom to simulate different internal organs inside the human body, (b) UWB phantom which covers ultra-wide band (3.1-10.6 GHz) frequency range, and (c) dynamic phantom to simulate the movement of the human body.

Keywords Physical phantom, Human body, Electromagnetic wave, Interaction

Advanced Physical Phantoms for Evaluation of Interactions between the Human Body and Electromagnetic Waves

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OUTLINE

1. Introduction
2. Physical phantoms
3. Examples of advanced physical phantoms
4. Conclusions and future works

Background

Increase in mobile communication devices

Increase in medical devices using EM waves

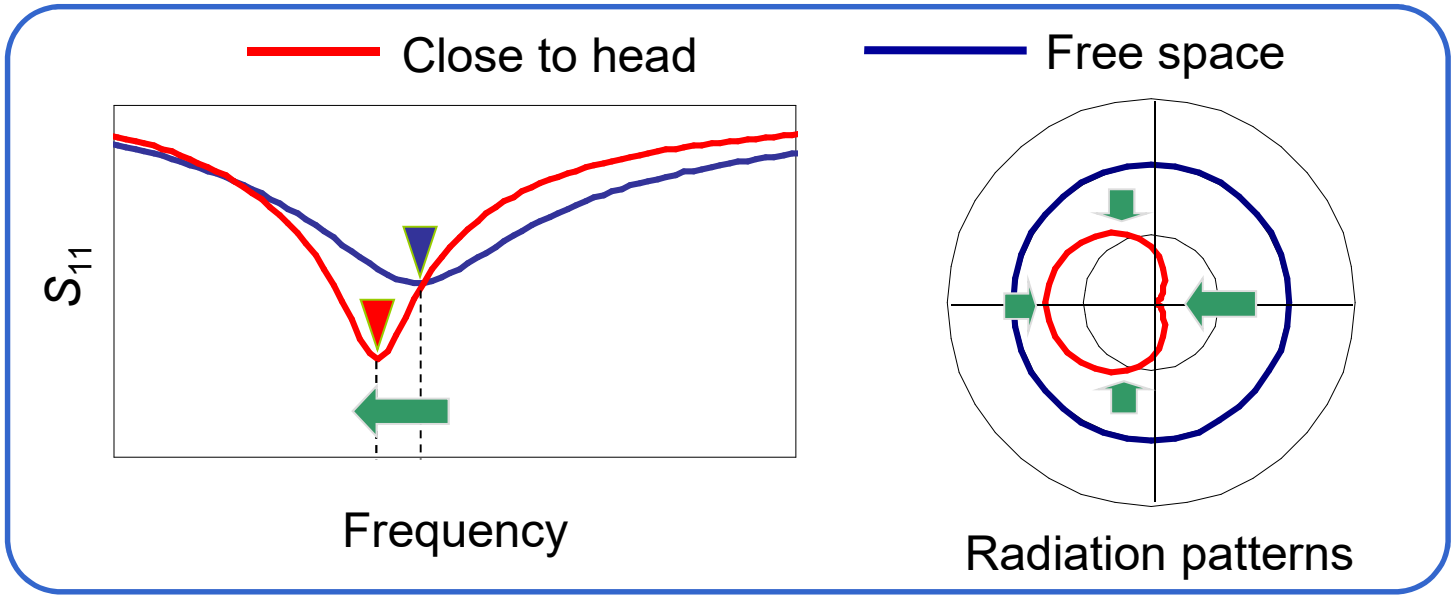
Necessity to evaluate the interaction between antenna (EM waves) and the human body

- **Human body ⇒ Antenna**
- **EM waves ⇒ Human body**

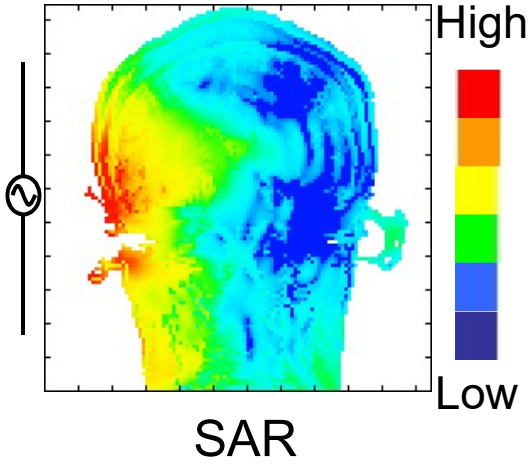
Effects of human body on antenna performance

Antenna close to human body

- Change of input impedance
- Change of radiation pattern
- Low radiation efficiency



Effects of EM waves on the human body



Absorption of EM waves

Generation of heat effect in human body

SAR (specific absorption rate)

$$\text{SAR} = \frac{\sigma}{\rho} E^2 \quad [\text{W/kg}]$$

E : Amplitude of the E-field (rms value) [V/m]
σ : Electric conductivity of the tissue [S/m]
ρ : Density of the tissue [kg/m^3]

Evaluation methods for such interactions

- Numerical simulation
- Experiments using **tissue-equivalent phantoms**

Performance evaluation of antennas / devices for *medical applications*

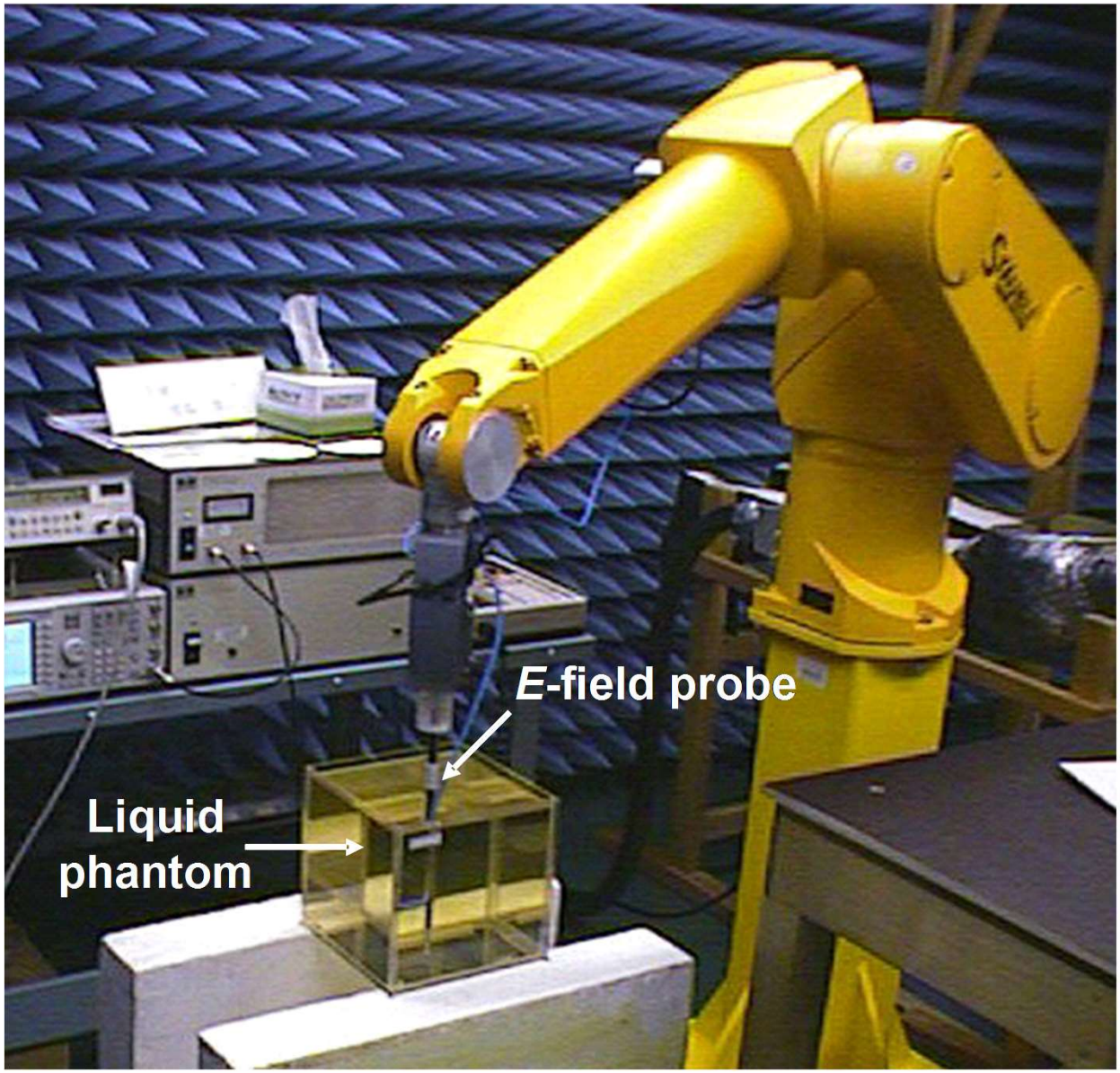
- **Numerical simulation (SAR, temperature)**
- **Phantom measurement (SAR, temperature)**
- ***Meat experiment***
- ***Animal experiment***
- ***Clinical treatment***

Physical phantom

Physical phantoms

- **Liquid phantoms**
  - Saline solution
  - Sugar and saline solution
  - Alcohol, etc.
- **Gel phantoms**
  - Polyethylene powder, TX151
  - Glycerol, etc.
- **Semi-hard (Semi-solid) phantoms**
  - Agar
  - Silicone rubber, etc.
- **Solid phantoms**
  - Ceramics
  - Resin, etc.

Example of liquid phantom



Example of liquid phantom filled in the shell

Courtesy of Dr. Ogawa, Panasonic, Japan

Rubber phantoms

Asahi Rubber Co. website

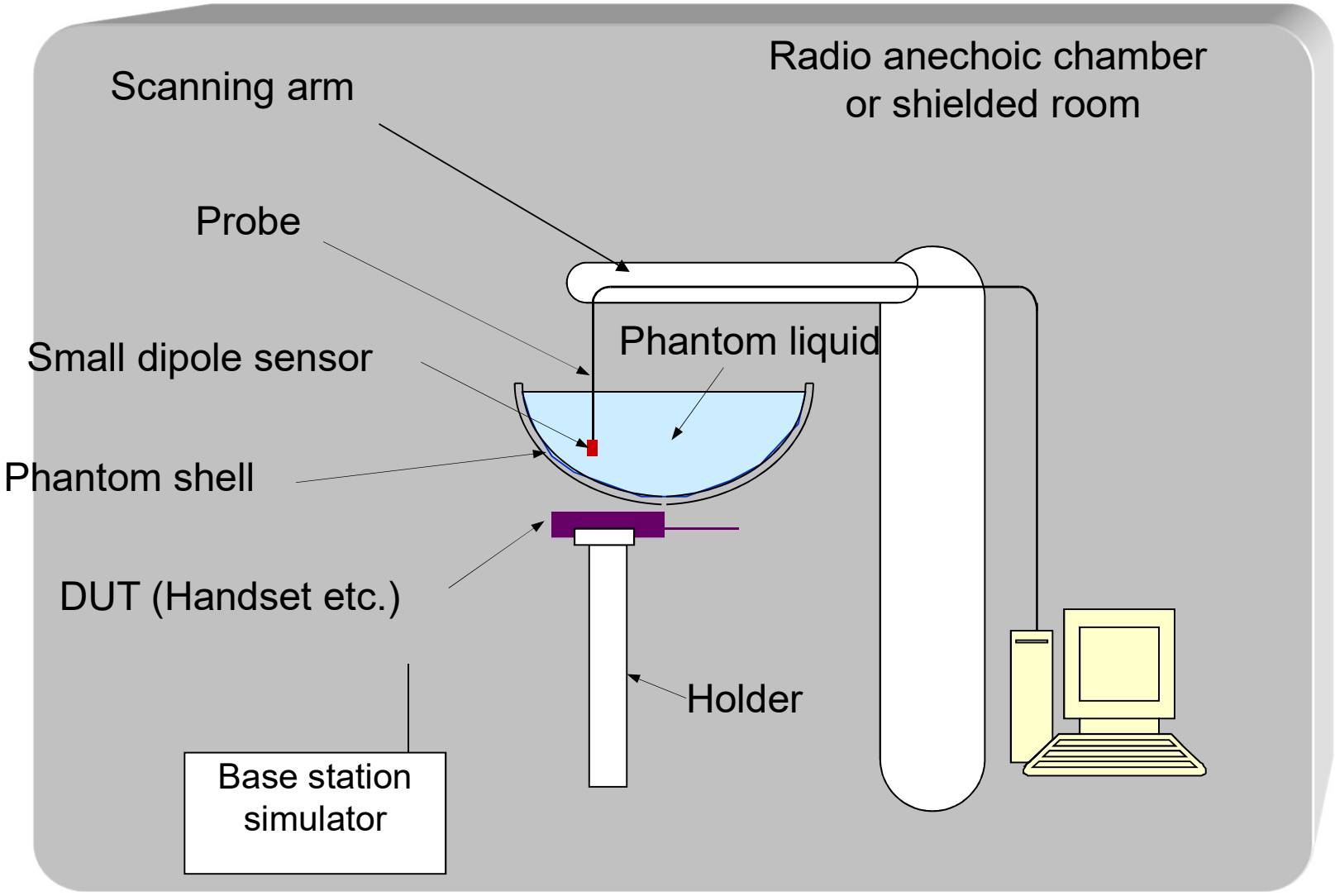
Example of *semi-hard* body phantom

A real-shaped body phantom is indispensable for achieving accurate evaluation of antenna characteristics.

The phantom can also be used for SAR evaluation.

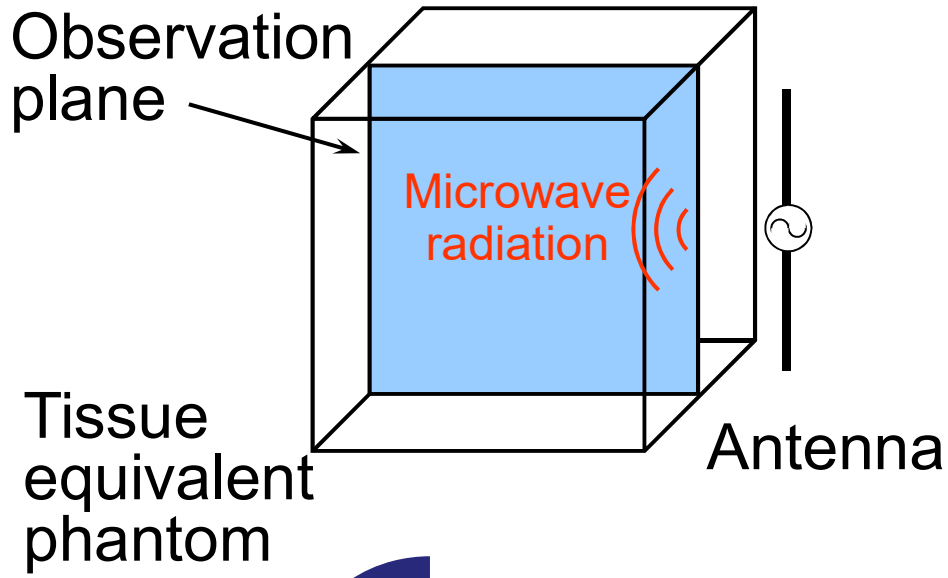
Future mobile satellite phone at 2.65 GHz

SAR measurement system



Courtesy of Dr. Hamada, NICT, Japan

The thermographic method



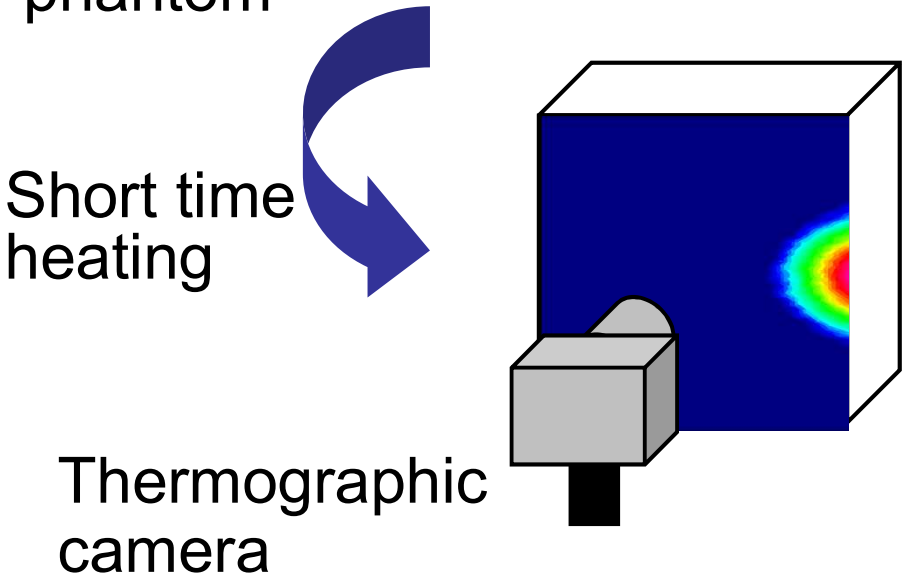
SAR (Specific Absorption Rate)

$$SAR = \frac{\sigma}{\rho} E^2 \quad [W/kg]$$

E: Electric field (r.m.s.) [V/m]

σ: Conductivity of the media [S/m]

ρ: Density of the media [kg/m^3]



Thermographic method :

$$SAR = c \frac{\Delta T}{\Delta t} \quad [W/kg]$$

c: Specific heat [J/kg·K]

ΔT: Temperature rise [K]

Δt: Heating time [s]

Typical evaluation methods for SAR

E-field method
(Liquid phantom)

Merits

1. Direct measurement of SAR is available
2. Actual devices can be evaluated

Demerits

1. Surface SAR is not measurable directly
2. It is difficult to measure SAR for small volume
3. It is difficult to realize multi-layered models

Thermographic method
(Solid or semi-hard phantom)

Merits

1. Surface SAR is measurable
2. Multi-layered model is feasible
3. Internal SAR for a complicated object is measurable

Demerits

1. Actual devices can not be evaluated because high power is needed
2. Care is necessary to estimate SAR of small specific heat materials

Advanced physical phantoms

- **Inhomogeneous phantom:** to simulate layered structure or internal organs
- **UWB phantom:** to cover UWB frequency range (about 3 to 10 GHz)
- **mm-wave phantom:** to cover mm-wave frequency range
- **Dynamic phantom:** to simulate the movement of the human body
- **Thermo-phantom:** to simulate temperature distribution
- **Ablation/coagulation phantom:** to simulate material changes with ablation or coagulation
- **Hybrid phantom:** ex. MRI + radiation

Implantable dipole antenna

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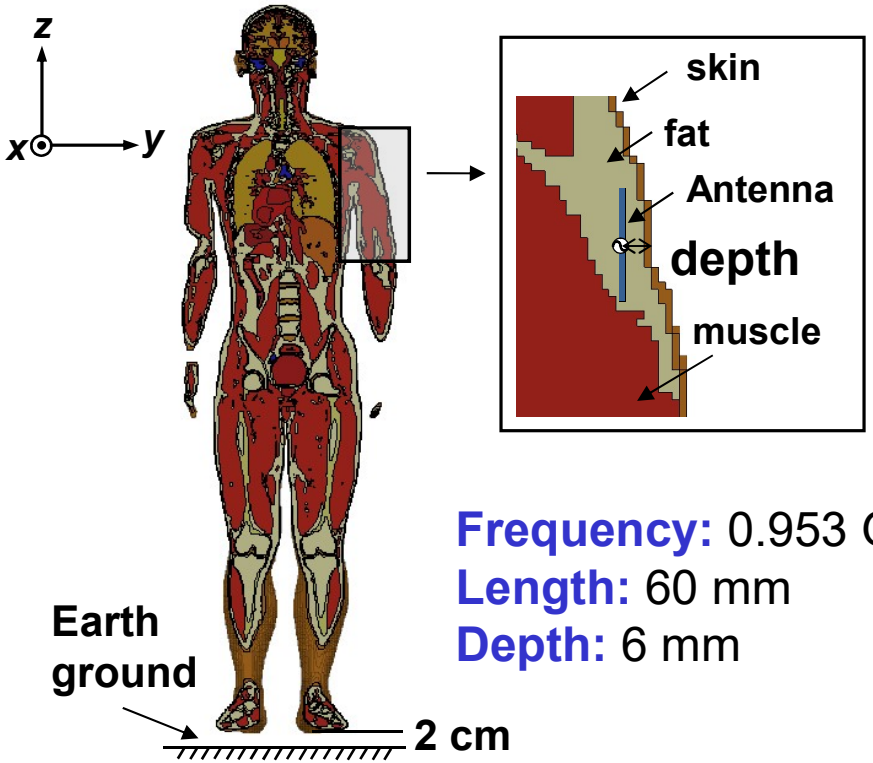
◆ **Antenna location and calculated result**

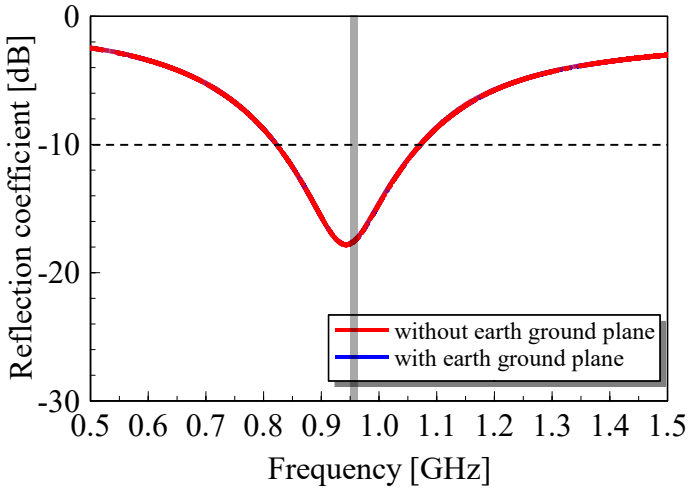
Antenna location

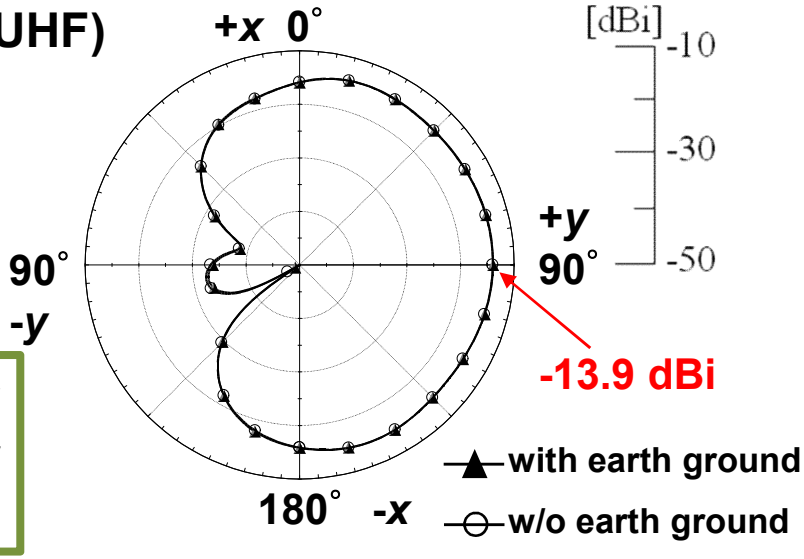


Frequency: 0.953 GHz **(UHF)**
Length: 60 mm
Depth: 6 mm

***Antenna is embedded into fat-layer.**

Antenna performance

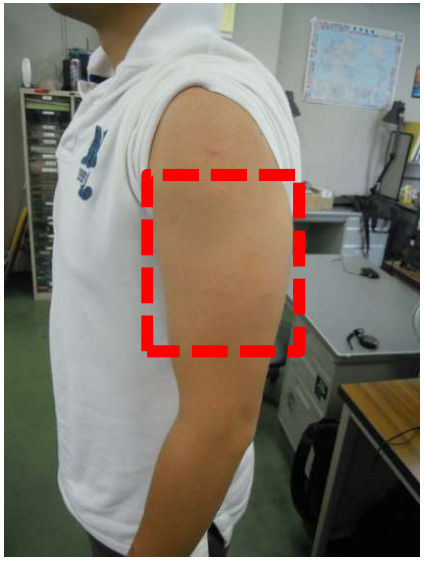




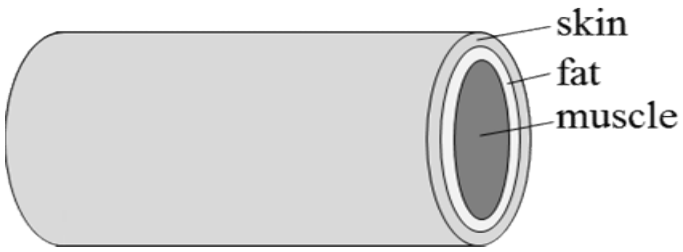
Antenna can cover the desired frequency band of 0.95 GHz, and EM waves are mainly toward +*y* direction.

Simple human arm model

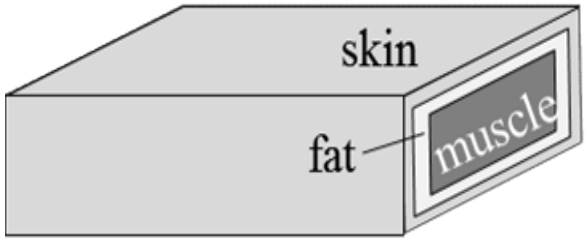
◆ Human phantoms are usually used to represent a realistic human arm for evaluation of implants



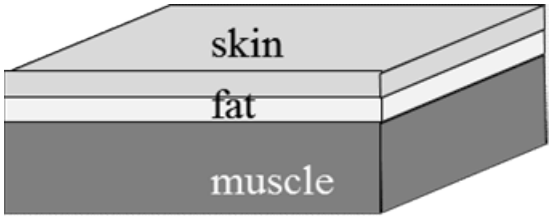
Realistic human arm



Cylindrical phantom



Rectangular phantom



Layered phantom

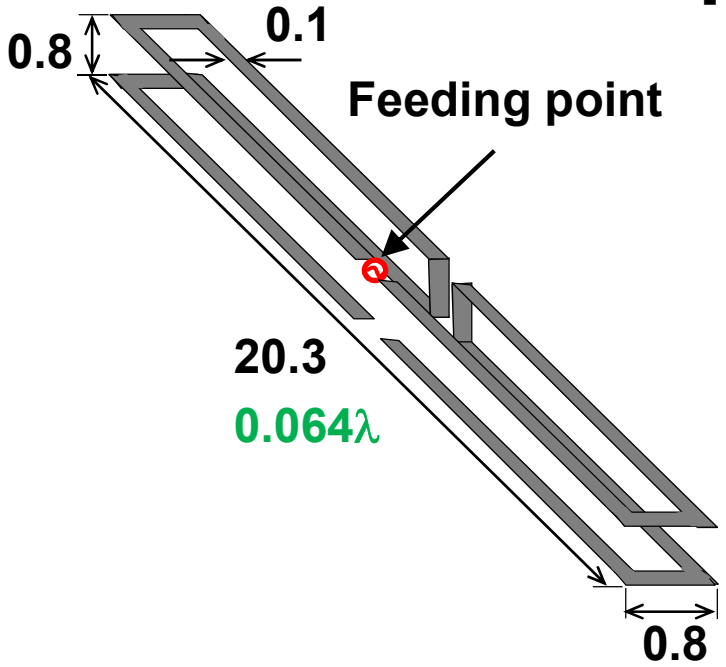
*Koichi ITO, "Human body phantoms for evaluation of wearable and implantable antennas," Antennas and Propagation, (EuCAP 2007), pp.1-6, 2007.
*Yumiko UNO, et al., "Structure of cylindrical tissue-equivalent phantom for medical applications," International Conference on Electromagnetics in Advanced Applications (ICEAA 2010), pp.406-409, Sydney, Australia, Sep. 2010.

Antenna design example

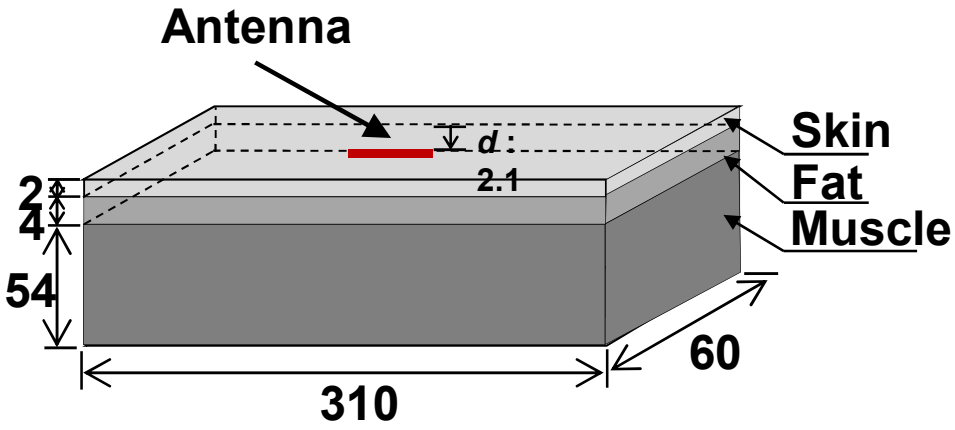
- **An implantable antenna with a cube-folded structure (0.95 GHz)**

Antenna structure

Unit : [mm]



Simple human phantom



Dielectric constant @ 0.953 GHz

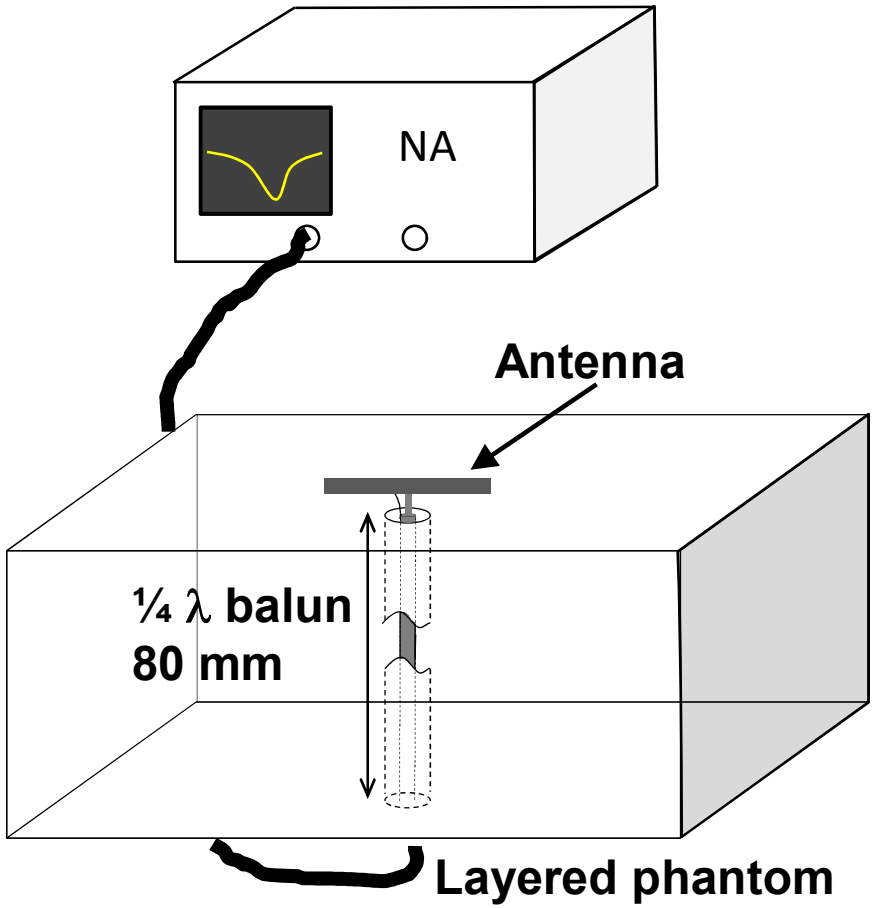
Tissues	ε_r	σ [S/m]
Skin	41.1	0.88
Fat	5.4	0.05
Muscle	54.9	0.96

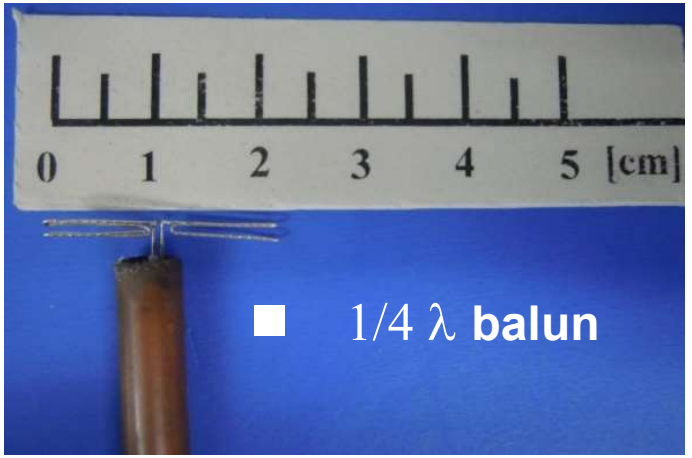
Whole size: 20.3 x 0.8 x 0.8 mm³
Width of radiating element: 0.1 mm
Feeding point: 50 ohms

*H. Y. Lin, M. Takahashi, K. Saito, and K. Ito, "Performance of Implantable Folded Dipole Antenna for In-body Wireless Communication," IEEE Transactions on Antennas and Propagation, vol. 61, no. 3, pp. 1363-1370, Mar. 2013.

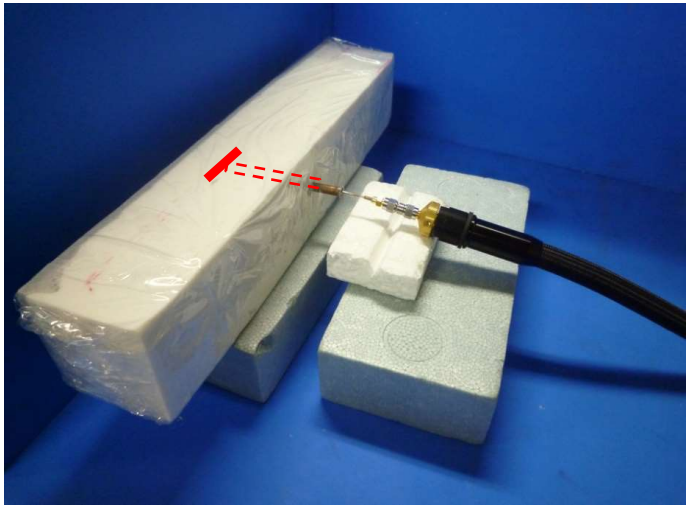
Measurement setup

- **Testing Input impedance**





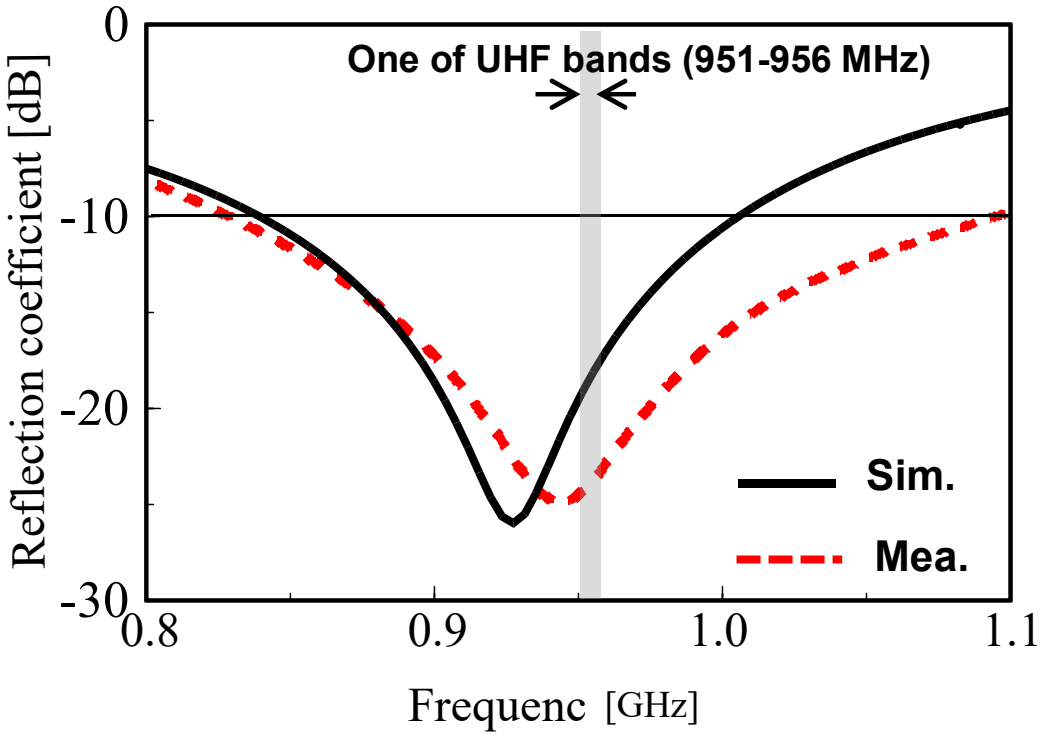
Fabricated antenna



Measurement view

Result and discussion

- **Reflection coefficient**



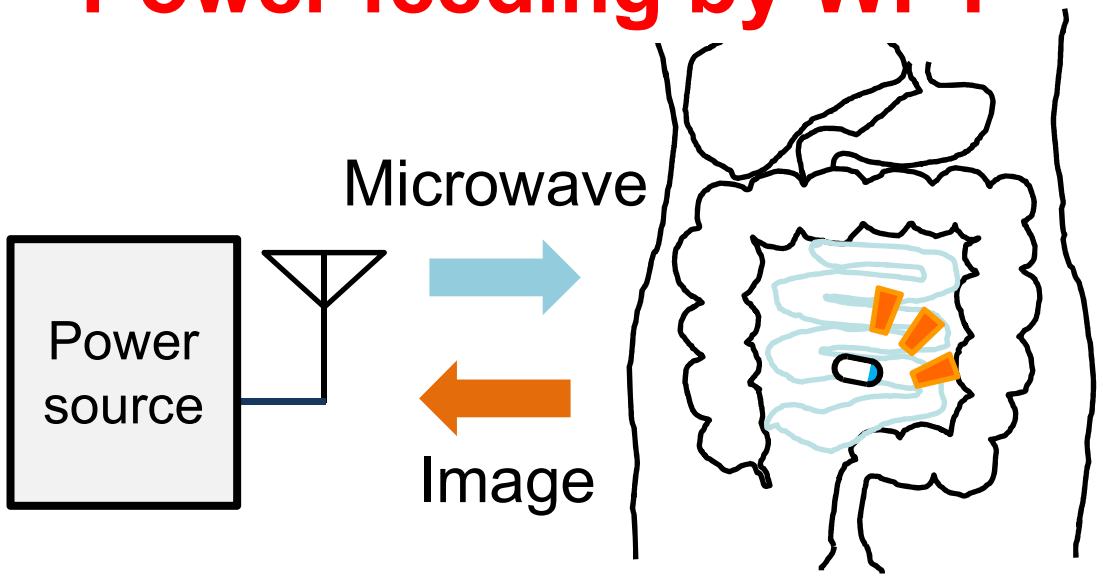
I. Desired frequency band of 0.953 GHz is fully covered.
II. The measured result is similar to the simulated one.

Antenna performance can be confirmed by measurement with semi-hard human phantom.

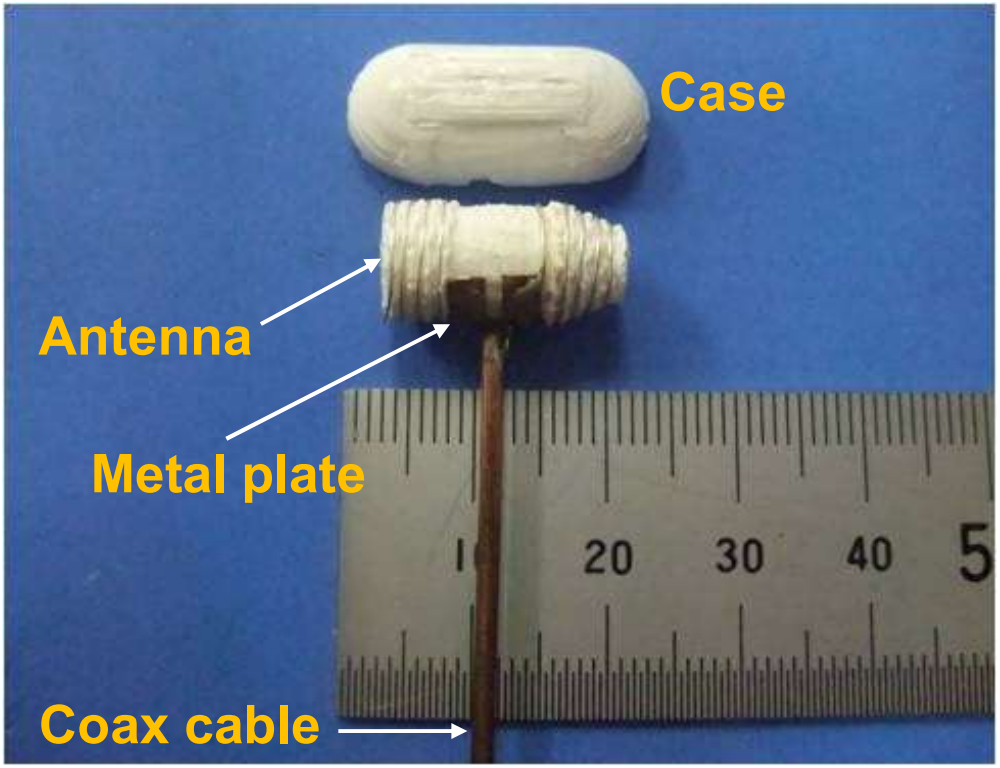
WPT to capsular endoscope

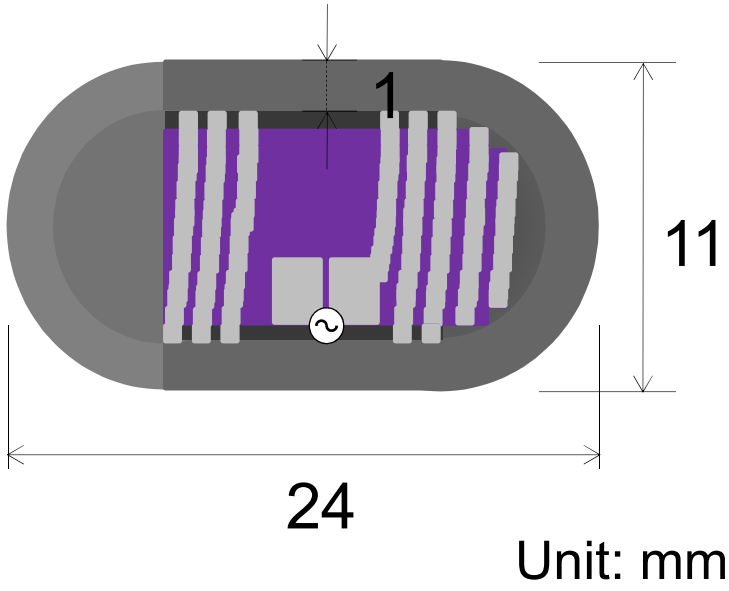
- Available energy in battery is limited
- Number of photos has restriction

Power feeding by WPT



Antenna inside the capsular endoscope



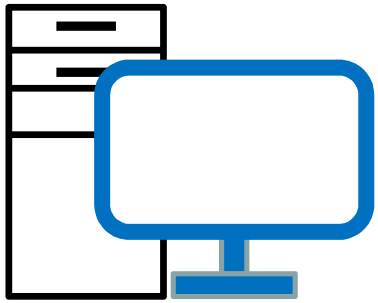


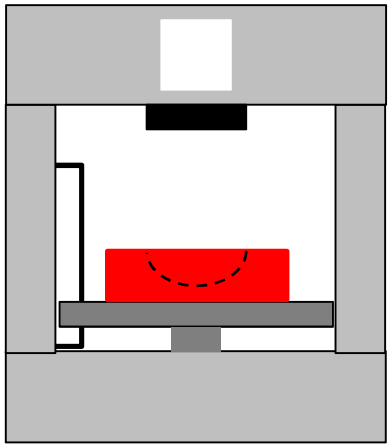
Fabricated antenna

Simulation model

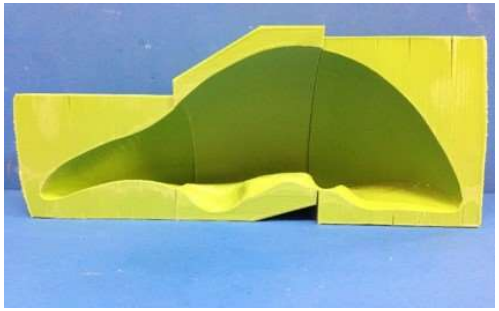
Molds for different phantoms

3-D data

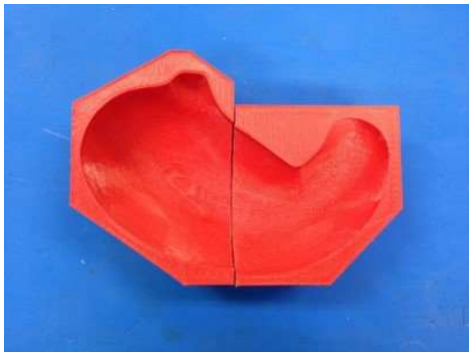




3-D printer



Mold for liver

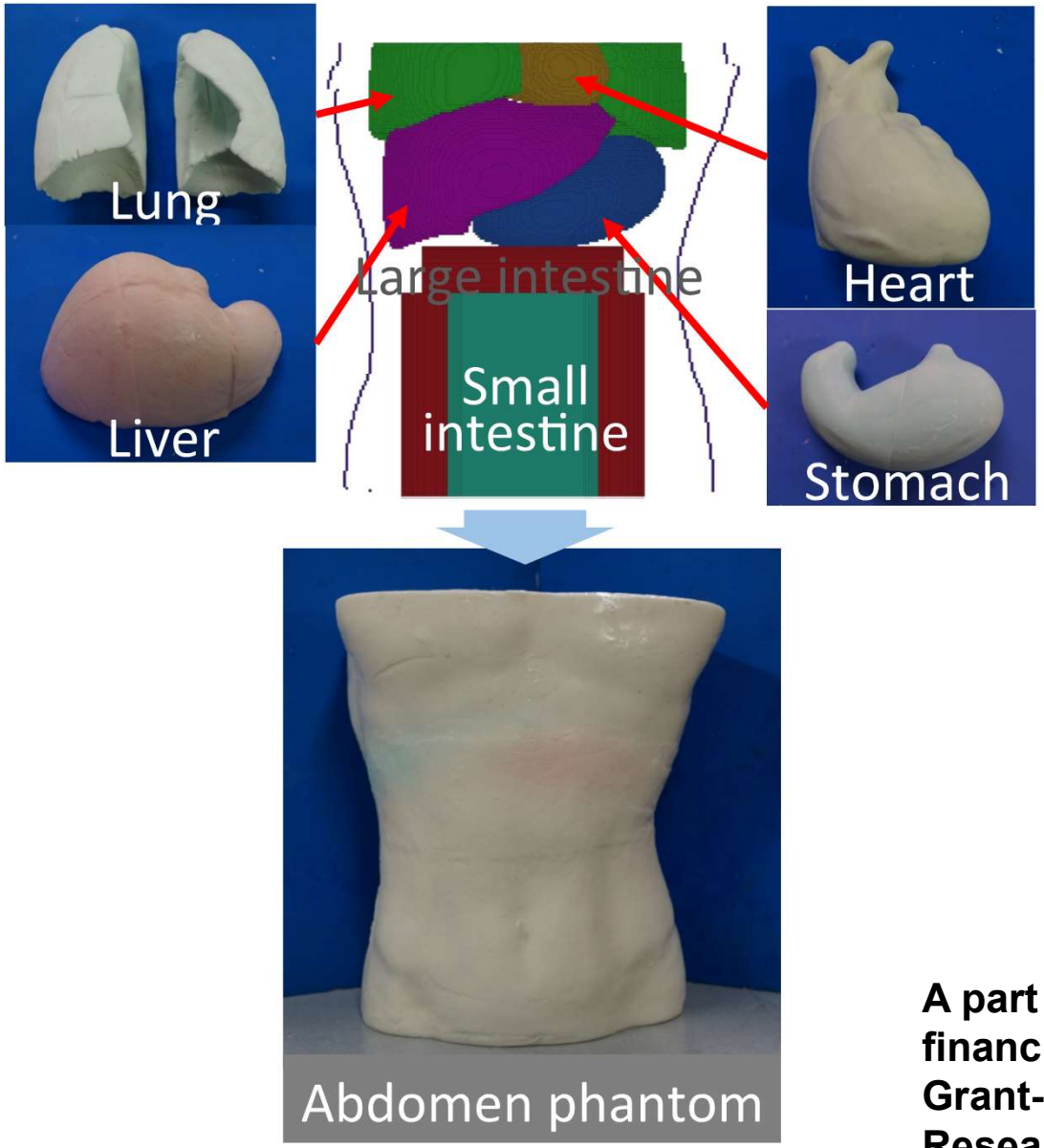


Mold for stomach

Electrical properties of the phantoms (target value)

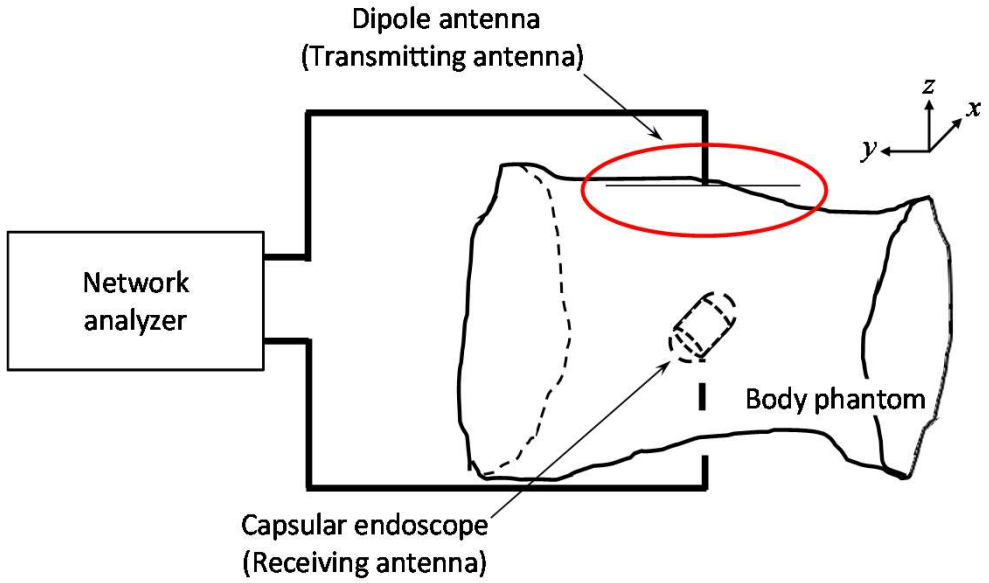
	Relative permittivity	Conductivity [S/m]
Muscle	57.7	0.83
Lung	Same as muscle	
Heart	Same as muscle	
Liver	50.7	0.67
Stomach	67.2	1.01
Large intestine	62.0	0.87
Small intestine	65.3	1.92

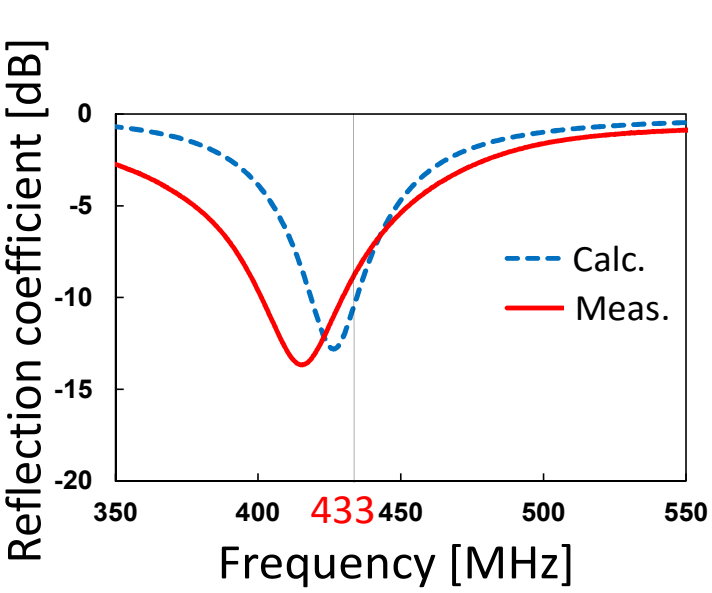
Fabricated inhomogeneous phantom

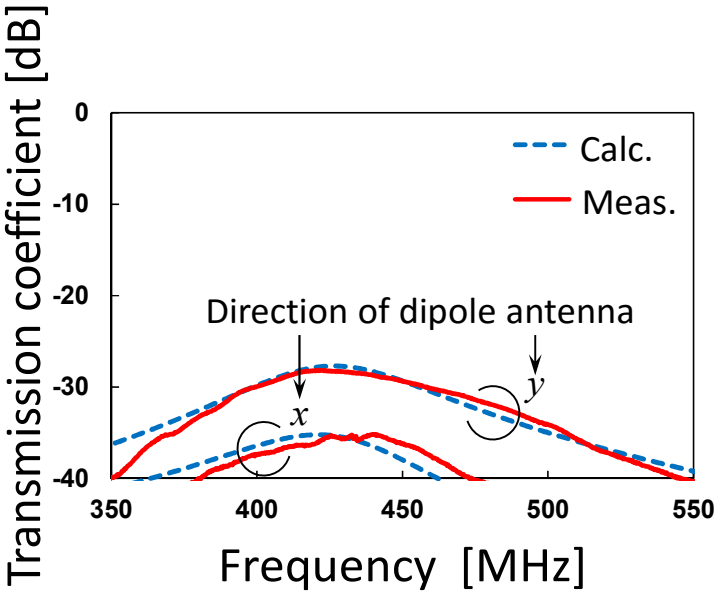


A part of this research is financially supported by Grant-in-Aid for Scientific Research (B) 24360132

S-parameters







A UWB phantom

- Wireless systems operating at 3 GHz or above popular
- UWB (Ultra Wide Band) technology developed

UWB communication systems :

used in the vicinity of the human body

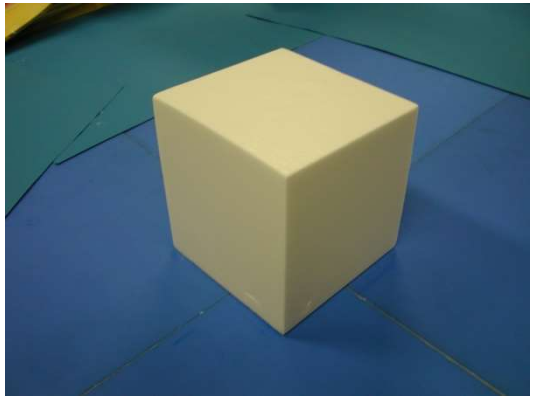
Biological tissue-equivalent phantom with higher frequency or broadband characteristics required.

New semi-hard phantom for UWB communications

A 2/3-muscle equivalent phantom

Material	Amount [g]
Deionized Water	3375
Agar	104.6
Polyethylene Powder	1012.6
Sodium Chloride	7.0
TX-151	30.1
Dehydroacetic Acid Sodium Salt	2.0

< A batch is approximately 4,500 g. >

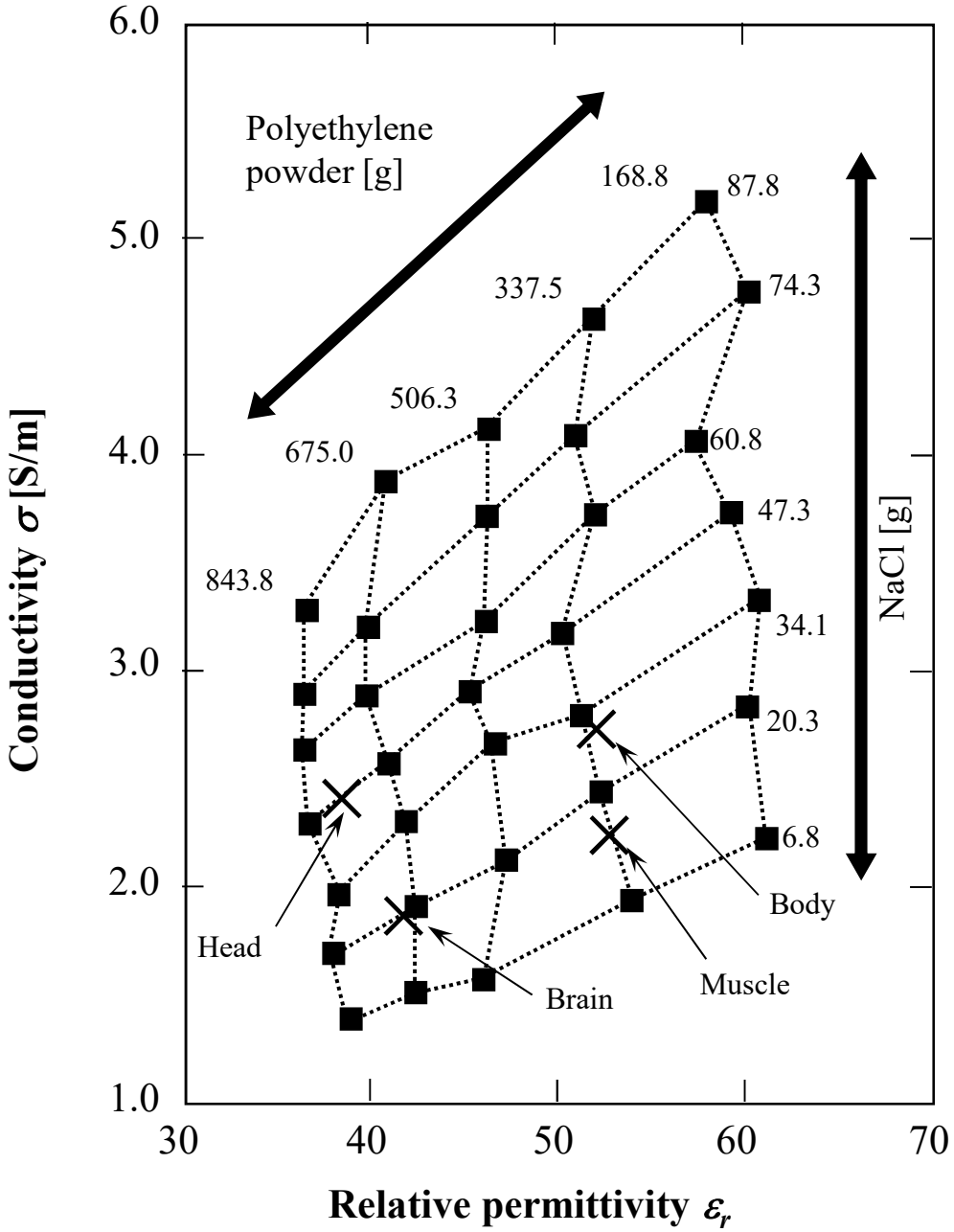


Phantom

Features

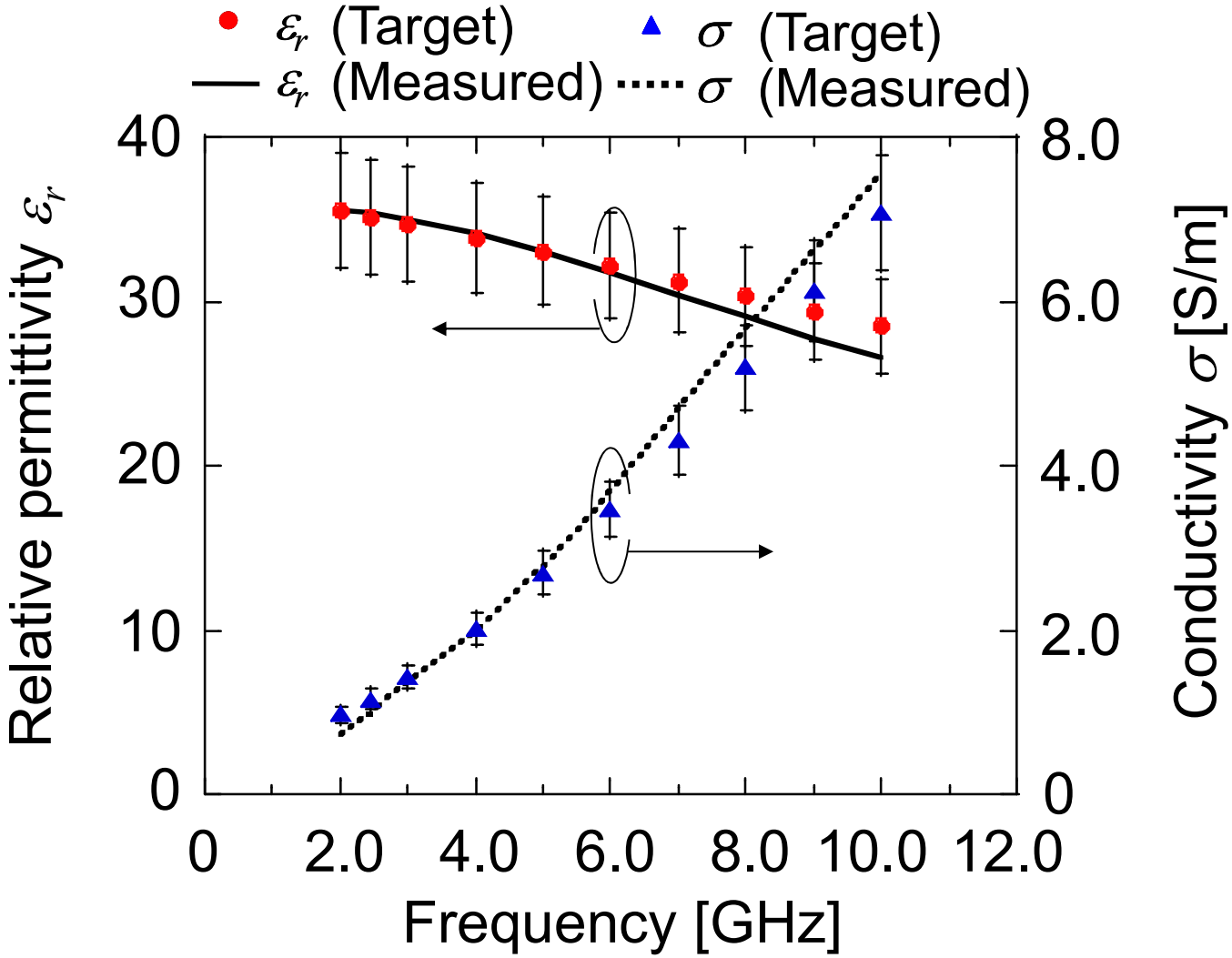
- Broadband above 3 GHz
- Easy adjustment of electrical constants
- Easy manufacturing of arbitrary shape
- Cheap and popular ingredients

Adjustment of electrical properties of the phantom



@ 3 GHz

Dielectric properties vs. frequency



*Target : 2/3 -muscle equivalent tissue

Sleep Monitor

Respiration during sleeping has received an attention for improvement of **quality of sleep**.

Conventional techniques

Pressure sensor

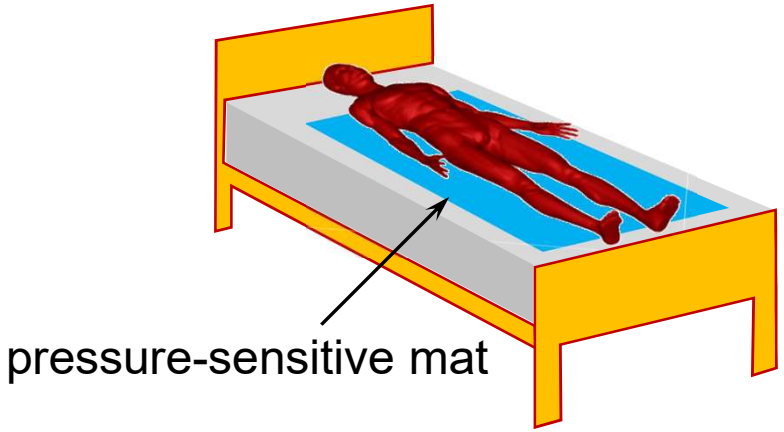
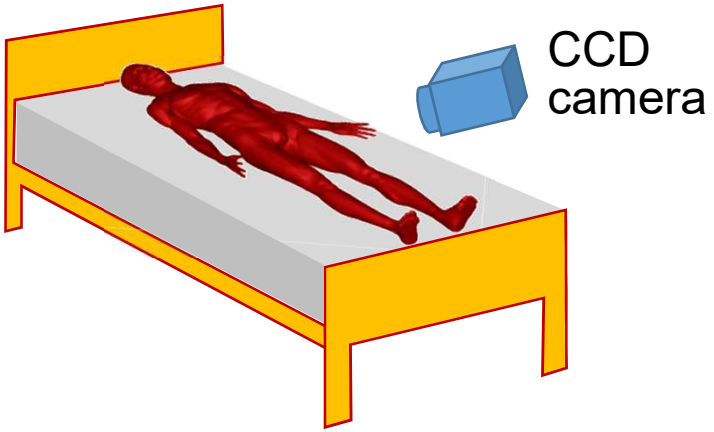
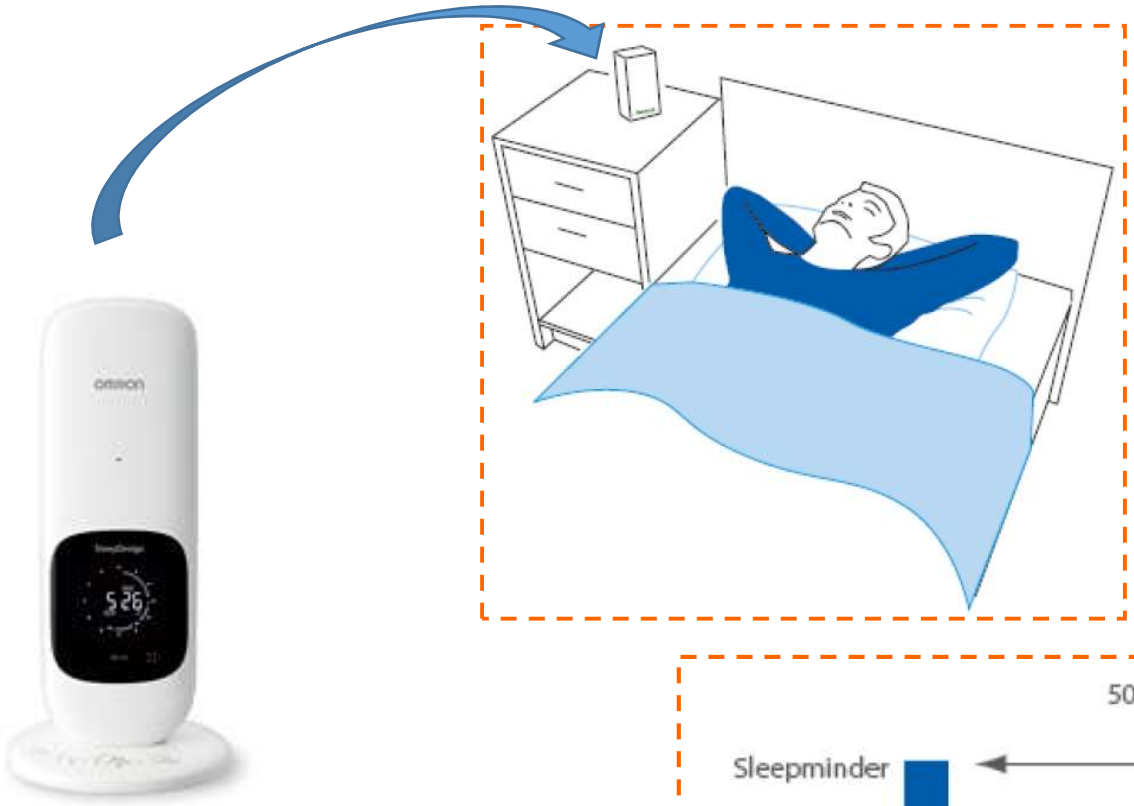


Image processing

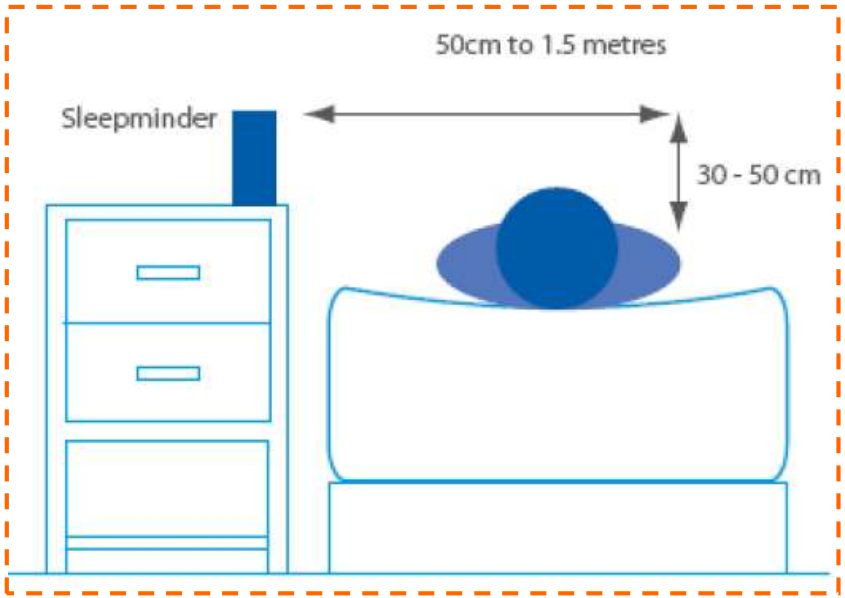


Microwave Sleep Monitor



10.525 GHz

Courtesy of OMRON HEALTHCARE Co., Ltd.



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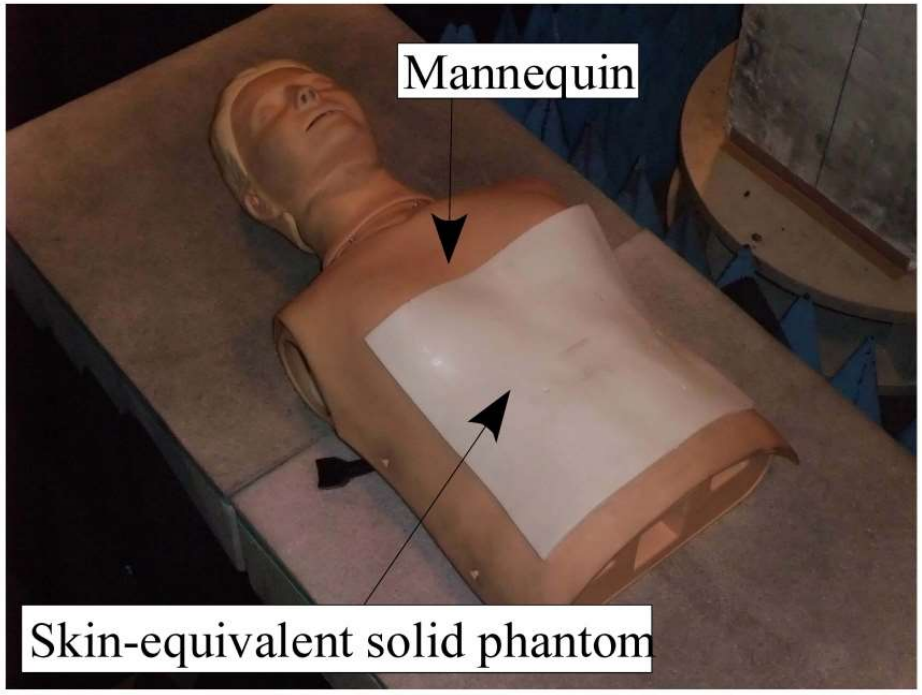
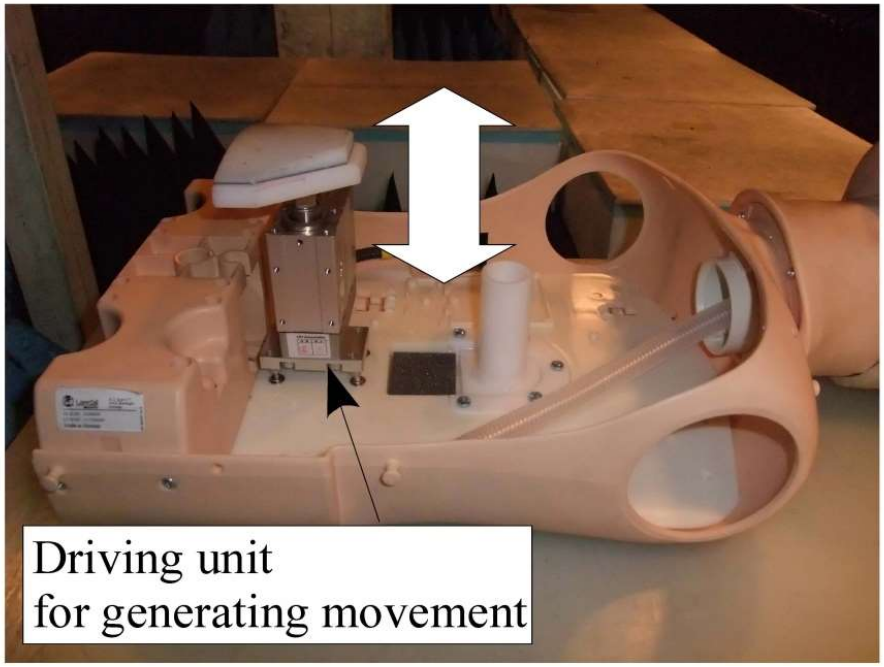
"Dynamic Phantom"

Simulates the body movement with respiration.





Yonebayashi, *et. al*., "Evaluation on Performance of Doppler Radar for Breath Detection by Dynamic Phantom", **AP-RASC'10**, Toyama, Japan, 2010

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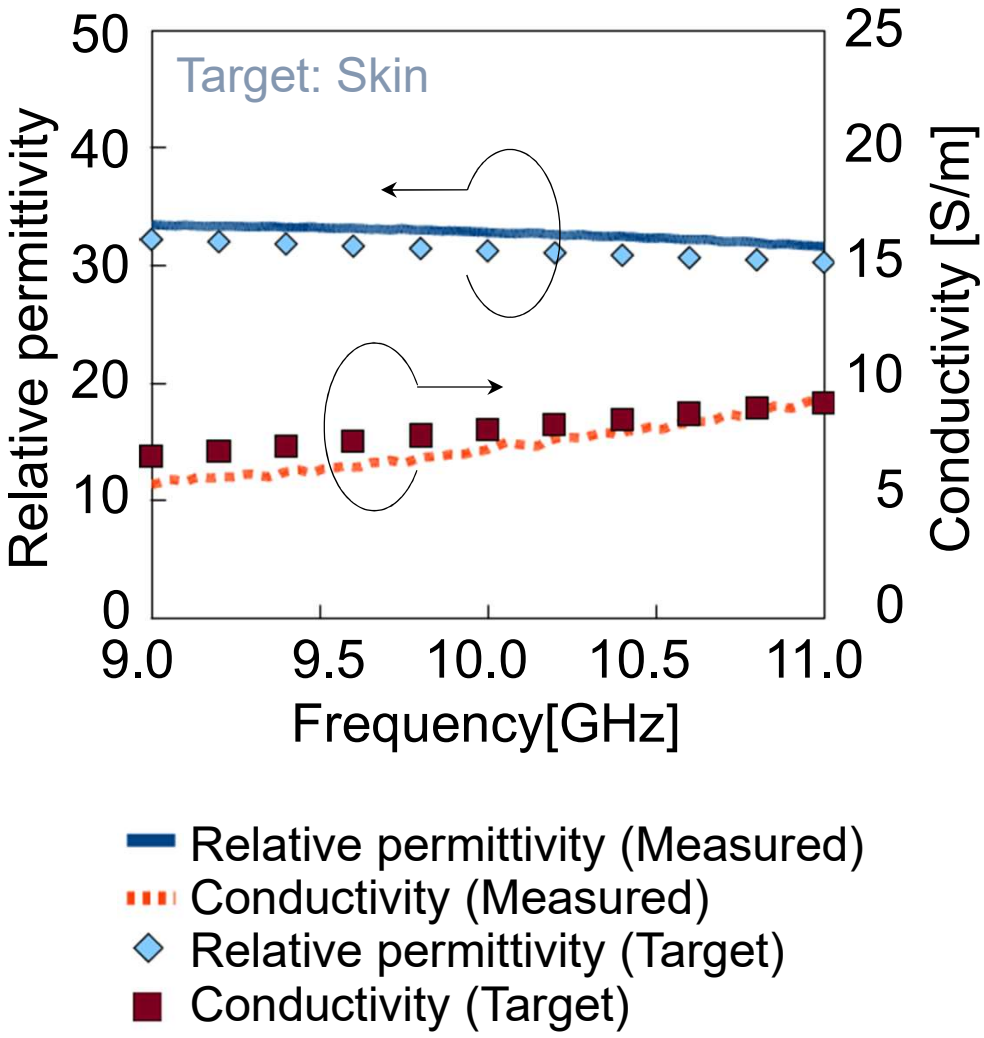
Electrical properties of *dynamic phantom*



Difference between measured and target values at 10.525 GHz is less than 10 %.

Electrical constants of skin-equivalent semi-solid phantom at 10.525 GHz.

	ε_r	σ [S/m]
Measured	32.4	8.1
Target*	30.8	8.6
Difference [%]	5.2	5.8

*http://niremf.ifac.cnr.it/tissprop/

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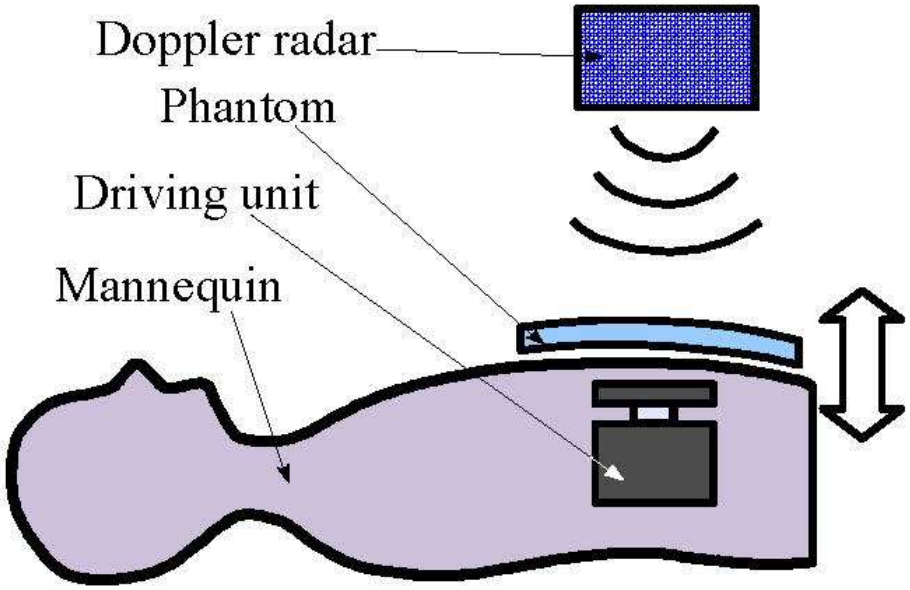
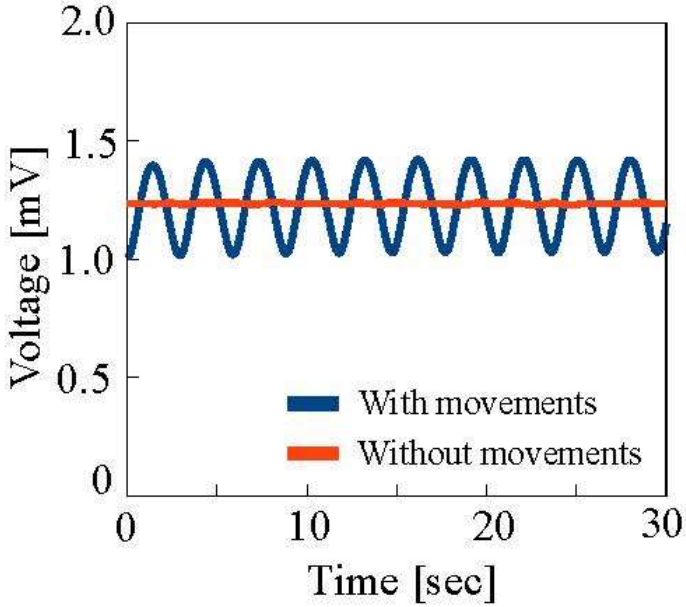
Output waveform of radar system



Measurement system



Output waveform

Yonebayashi, *et. al*., ”Evaluation on Performance of Doppler Radar for Breath Detection by Dynamic Phantom”, **AP-RASC’10**, Toyama, Japan, 2010

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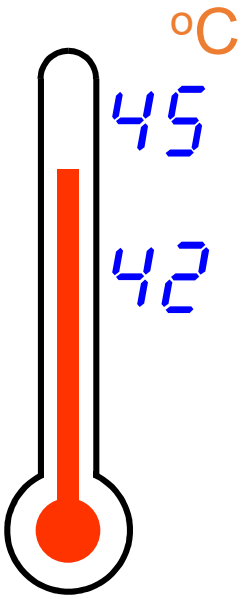
Future works

Advanced Physical Phantoms

- Inhomogeneous phantom: to simulate layered structure or internal organs
- UWB phantom: to cover UWB frequency range (about 3 to 10 GHz)
- mm-wave phantom: to cover mm-wave frequency range
- Dynamic phantom: to simulate the movement of the human body
- **Thermo-phantom: to simulate temperature distribution**
- **Ablation/coagulation phantom: to simulate material changes with ablation or coagulation**
- Hybrid phantom: ex. MRI + radiation

Hyperthermia



Decrease of the ratio of survival cancer cells

Little damage to normal cells

Effect of radiotherapy or chemotherapy enhanced

No side effect

40 – 42 C : *"Mild hyperthermia"*

Heating schemes

- **Internal heating (interstitial / intracavitary)**
- **External heating**

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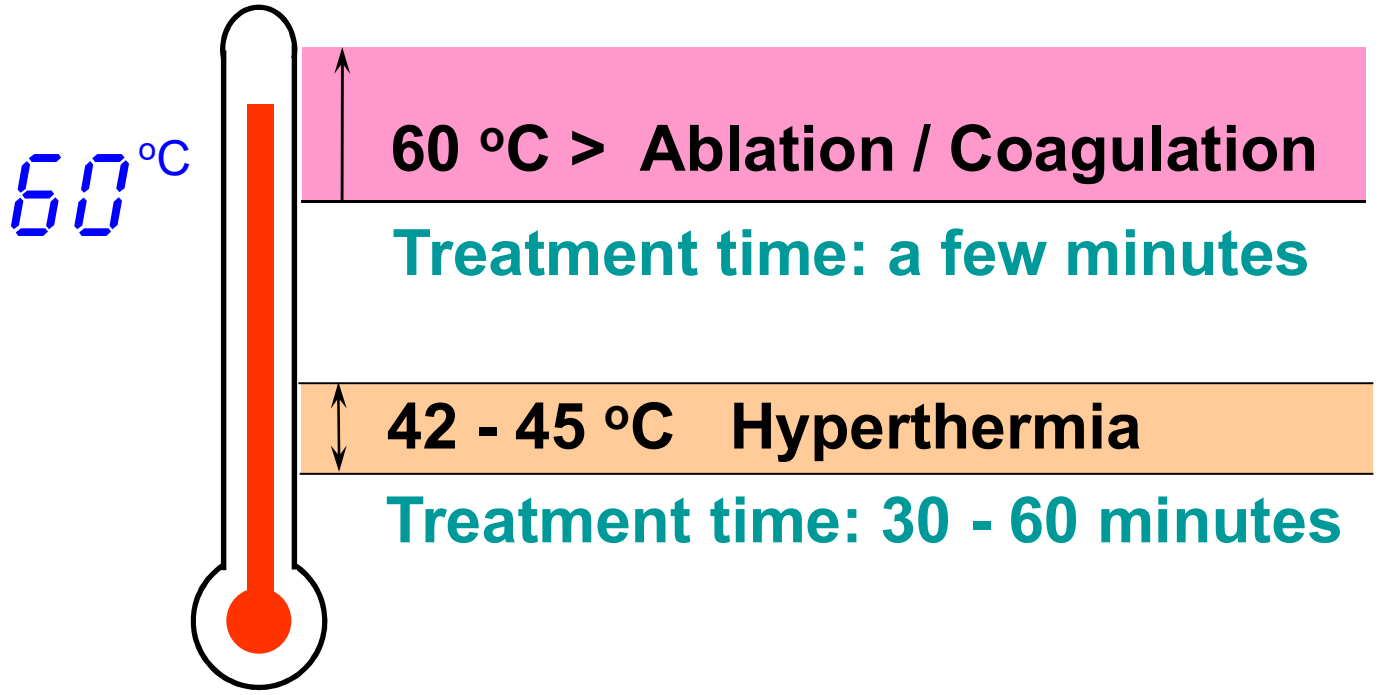
Radio Frequency Ablation (RFA)
Microwave Coagulation Therapy (MCT)



Target: small size cancer (< 3 cm)
(e.g. hepatocellular carcinoma)

Merits: minimally invasive
short time heating

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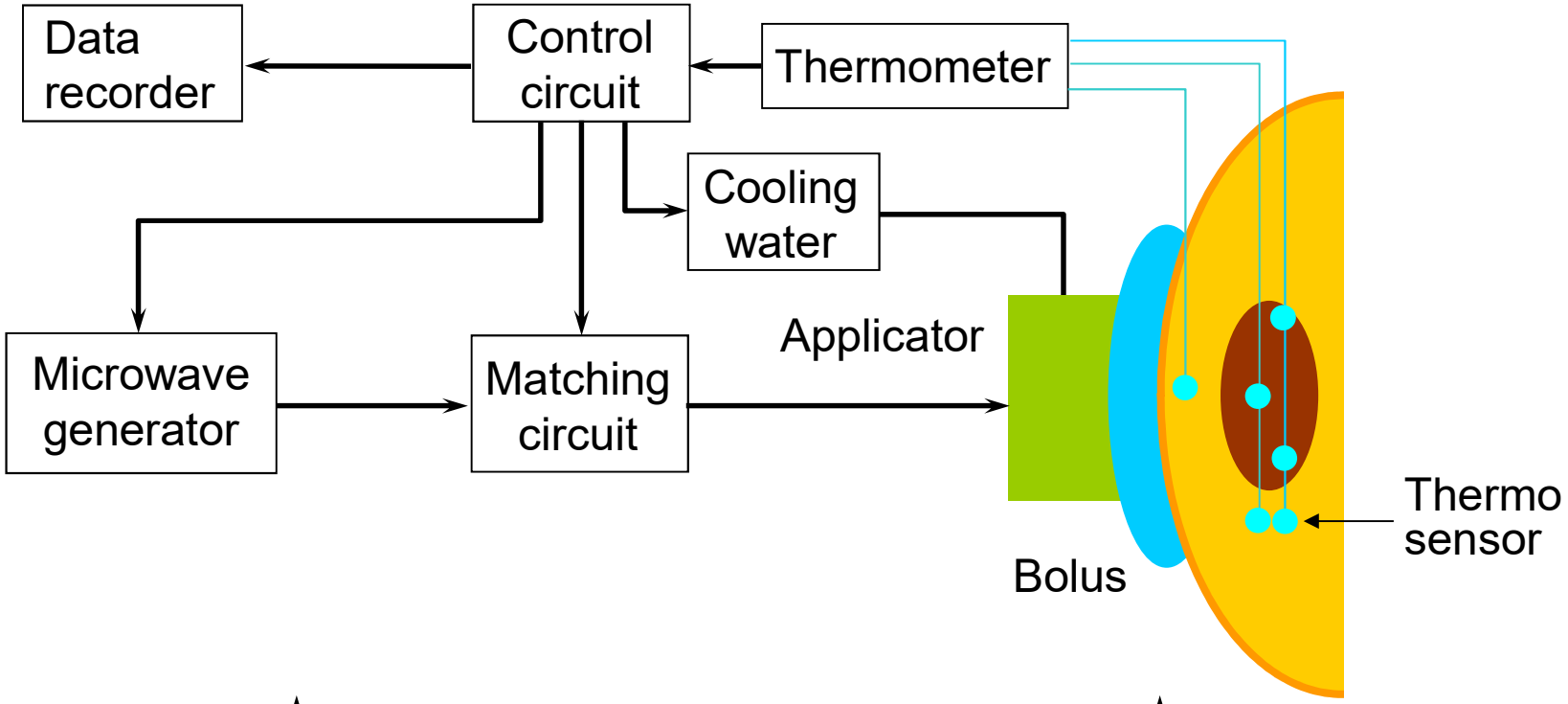
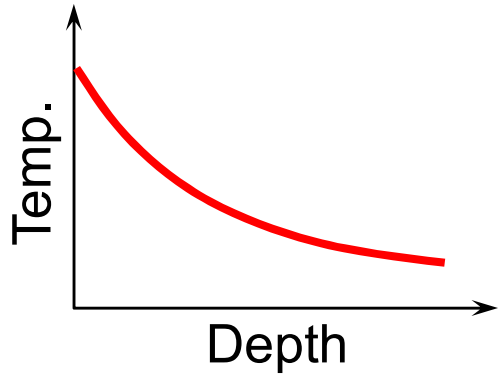
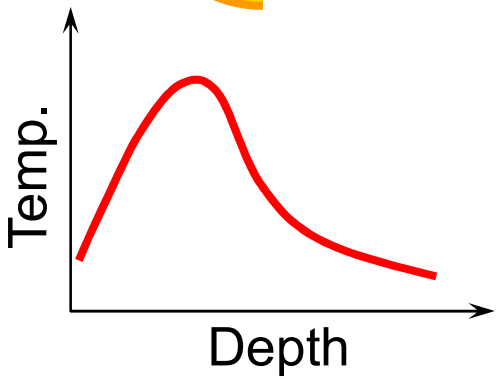
Microwave external heating system



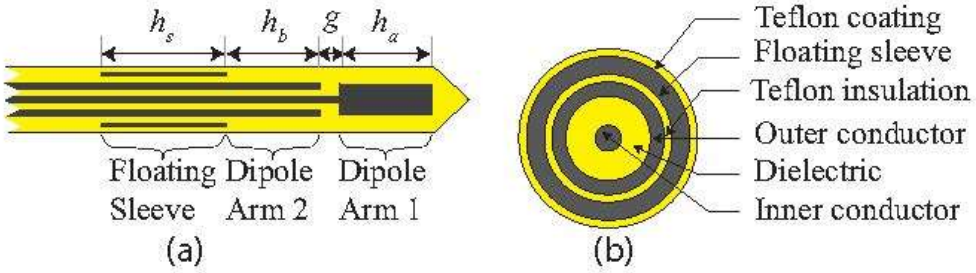
Without surface cooling



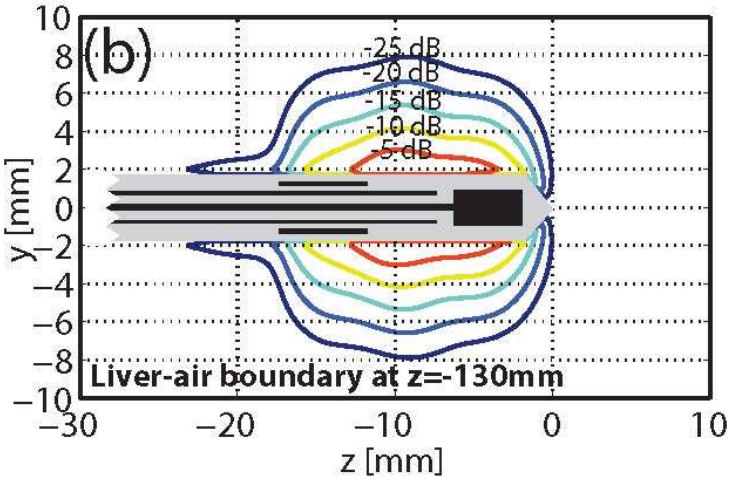
With surface cooling



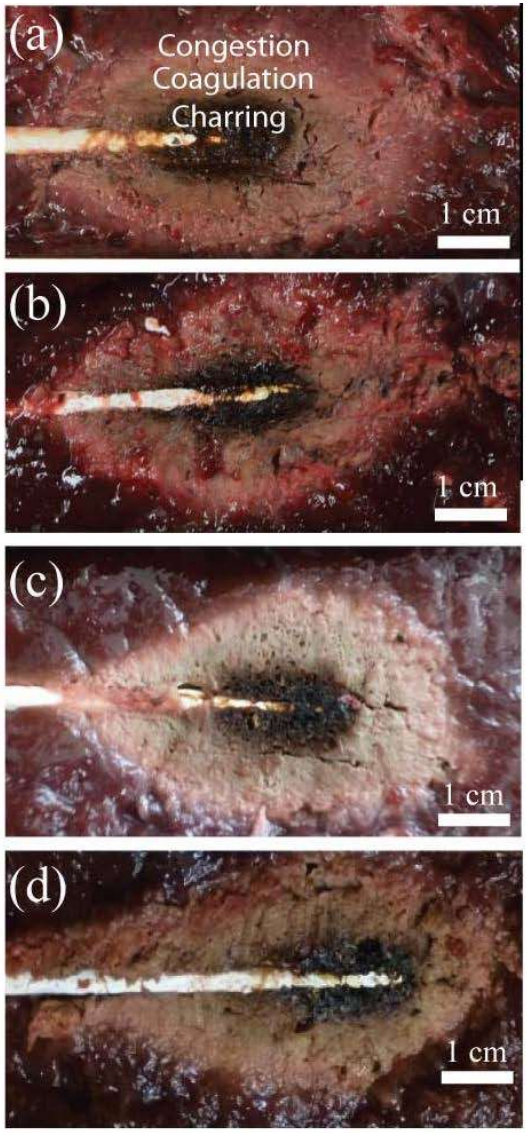
High Frequency Microwave Ablation (10 GHz)



Antenna structure



Simulated SAR pattern



Bovine liver experiments

Luyen, Gao, Hagness and Behdad, "High Frequency Microwave Ablation for Targeted Minimally Invasive Cancer Treatment," Proc. **EuCAP2014**, pp.1828-1832, The Hague, April 2014